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OF THE 1976-1977 U.S. DROUGHT

by

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Hamid Fakhraei, Herbert H. Fullerton,
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ABSTRACT

Three approaches to drought management are developed as generalized mathematical models. Each model is then applied to particular locations in Utah using the hydrologic/economic data from the 1976-77 drought. The modeling approaches include:

(1) A multiple regression approach is used to quantify the changes in water use achieved by three common municipal sector rationing policies:

  (a) restrictions on time of outdoor use,
  (b) price increases, and
  (c) mandatory quantity restrictions.

(2) A model was presented for determining the optimal long term price schedule for rationing a stochastically variable water supply during summer peak demand season among groups of municipal water users which have different demands.

(3) The third model analyzed various management policies in terms of their impact on net benefits to the agricultural and municipal sectors. The model is capable of modifying policies monthly, based upon the changing hydrologic situation. It can vary constraints in a manner that simulates an institutional environment ranging from total freedom of price changes and water exchanges between sectors to those constraints existing during the 76-77 drought.

Conclusions include: 1) Mandatory water use regulations are much more effective than price increases in reducing water use (at least in a short term drought). 2) A theoretical analysis of demand and supply functions showed that Salt Lake City's pricing policy (about $0.25/1000 gallons) is very close to optimal. 3) The third model showed that very substantial losses in consumer surplus in Salt Lake County during the drought were caused by various institutional restrictions.

ACKNOWLEDGMENTS

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Chapters I and V	- Trevor Hughes
Chapter II	- Rangesan Narayanan, Trevor Hughes, and Dean Larson
Chapter III	- Hamid Fakhraei, Rangesan Narayanan and Herbert Fullerton
Chapter IV	- Mac McKee and Bruce Bishop
Appendix	- Dean Larson and Trevor Hughes

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CHAPTER I

INTRODUCTION AND SCOPE OF REPORT

Nature of Drought Planning

It is not possible to plan for drought in isolation from general water resources planning. The objective of a rational manager of a water supply system should be to develop facilities which can be operated to maximize net benefits from a long term perspective--considering the relative probabilities of wet, average, and drought years. An optimal plan may, for example, anticipate a drastic reduction in production (perhaps to zero) if the cost of water exceeds its value during an infrequent drought period. In fact, the economic justification for new facilities is largely based on reducing the frequency and severity of these reductions.

Once a drought period has begun (and more importantly has been recognized as having begun--which is not a trivial task), water management takes on a short run operating perspective. One problem is that of guessing how short the perspective should be. A reservoir operator, for example, must decide whether to release all needed storage during the current high demand summer season (thereby assuming the drought will terminate after one season) or to carry some over for use during an extended drought. This decision must be made in an environment of great uncertainty (no one can predict multi-year weather patterns) and great pressure from water users who may already be suffering losses. Dealing with this uncertainty is the essence of the drought water management problem.

During the winter of 1976-77, many western areas experienced the lowest precipitation totals on record. The most serious previous drought in most of these areas began in 1931 and lasted until 1934. The 1976-77 drought lasted only one year, but an enormous drought relief effort, for example an $844 million "drought package" on the federal level, resulted.

Droughts produce the best possible political environment in which to finance water development projects. Often, low interest loans and even grants become available from federal and state sources and convert marginal projects into profitable projects from the perspective of the subsidized users. Opportunistically, water development interests may best plan for drought by stock-piling project designs for financing during the next drought.

Drought is difficult to quantify. One difficulty in determining drought severity is that it cannot be generalized. Even in a region where climatic drought conditions are uniformly serious, the impact upon water users is highly site specific (Bowles et al. 1980). Drought severity and vulnerability are functions of many factors besides the reduction in supply. Some users acquire water rights which significantly exceed their average-year requirement in order to insure the desired supply during a dry year. Others experience serious shortages. The type of water source is very important in terms of vulnerability to drought. Run-of-river users are impacted first, users with reservoirs may not be severely impacted unless a drought becomes lengthy, and groundwater users are best insulated.

Scope of Report

A rather extensive literature came out of the 1976-77 drought, most of which is historical in nature--how serious was the drought and how did water users and various levels of government respond. This report attempts to use such information by analyzing it on two different levels:

1. The historic data will be used to develop a regression model quantifying the effectiveness of various drought management actions taken.

2. Two optimization models will also be developed for analyzing various drought management concepts (which may or may not have been used during 1976-77).

All three models will be applied hypothetically to the 1976-77 situation in order to provide quantitative guidelines for future drought management. The three models are presented in the next three chapters.

Chapter II begins with a summary of actual 1976-77 drought response mechanisms and their use at various levels in each of several water using sectors in several states. A regression analysis of the effectiveness of such policies for the municipal sector is presented. The regression model appears to have a rational theoretical basis and, therefore, should be useful for future drought management planning applications.

Chapter III presents a model for rationing of water during drought. A basic assumption here is that simply varying the price of water to match supply and demand is not a viable policy due to various political/social considerations. Instead, a relatively long term pricing policy combined with short term quantity rationing rules is suggested for maximizing social welfare given the stochastic nature of water supply. This model is applied to the Salt Lake City municipal system.

Chapter IV presents a multiple sector (municipal/industrial and agricultural) model for drought management. The objective of this chapter is to compare the economic consequences of the water management policies followed in Salt Lake County during the 1976-77 drought to those which are identified by the model as being socially optimal. This model has the capability of predicting optimal operating policies (updated monthly) given historic hydrologic data.

Organization of Literature Review

The literature on drought related research and management of the 1976-77 drought will in general be cited and discussed in Chapters II, III, and IV as specific topics are covered. However, some of the literature which is not discussed in subsequent chapters will be described briefly here:

1. Weather modification: A significant on-going research effort is being sponsored by the U.S. Bureau of Reclamation and by NOAA. This Southwest Drought Research Program has produced several reports related to the technical and economic potential for reducing drought severity by weather modification. These include:

Bowles et al., 1981: Development of Contingency Plans and Scientific Background Studies for Applying Weather Modification during Drought Periods in Utah.

Buller et al., 1981: Effect of Weather Modification on Supply of Total Revenue of a Region.

U.S. Bureau of Reclamation, 1981: Southwest Drought Research Program.

2. James, D. J. and Wade H. Andrews, 1978: Water Conservation Information Dissemination During the 1977 Drought Emergency.

This study was organized during 1977 to provide, for the exchange of drought information among the respective states, a forum that could reduce duplication among independent efforts. The project collected information on: a) water-use conservation practices; b) water-supplies; c) dealing with special drought problems. Types of information included: 1) research results contributing to dealing more effectively with emergency drought situations; 2) research currently underway; 3) brochures or other material prepared for public distribution; 4) reports of extension agents or other technical personnel working with the public to solve drought problems; and 5) user or expert statements recommending supplementing or revising any of the above. This report contains 667 abstracts and a synthesis of the information obtained on each topic.

3. Institute for Policy Research, 1977: Directory of Federal Drought Assistance.

This report, for the Western Region Drought Action Task Force, describes more than 40 loan and/or grant type drought programs which are administered by 15 agencies. The report also cross-indexes drought problems with appropriate programs.

4. Rosenberg, Norman J. (editor), 1978: North American Droughts.

This collection of seven papers covers a broad range of drought-related topics including: a history of American drought; concepts for measuring severity and economic, political and social impacts; and management strategies.

5. Dyke, Paul T., 1977: Yield Response Handbook.

This handbook describes use of the "National Crop Yield Simulator" which has been developed by the Economic Research Service. The simulator provides a methodology for calculating crop yield changes as a function of drought severity in any area of the U.S.

6. Federal Power Commission-Federal Energy Administration, 1977: Impacts of the Western Drought on the Regional Electricity Situation.

This report analyzes the sensitivity of western energy costs to drought conditions. The critical proximity of demand to supply capability during both winter and summer peaks is described. Both short- and long-term recommendations for relieving the problem during future droughts are given.

CHAPTER II

SUMMARY OF 1976-77 DROUGHT MANAGEMENT RESPONSES AND REGRESSION ANALYSIS OF POLICY EFFECTIVENESS

Drought Impact Response in 1976-77

A fairly large literature on the 1976-77 drought provides substantial information on the techniques used to mitigate drought impacts. The present need is to integrate the descriptive information on programs and effects in a variety of communities with a model that contributes to an overall understanding that can contribute to more effective program design for future droughts. The report attempts to do so by beginning with the conceptual model of Figure 1.

The five traditional water use sectors shown in the upper left corner of Figure 1 are natural choices for grouping drought program impacts. They tend to be institutionally distinct and coherent interest groups capable of mobilizing political support for programs they favor at national, state, and local levels. Consequently, they are typically identified as the target group of public policy. In the present discussion, emphasis is placed on the municipal, domestic, and agricultural sectors because the drought experiences of the other three are difficult to generalize or were not the object of extensive mitigation efforts.

Drought mitigation initiatives can be taken at the federal, state, or local level of government or by individual water users for their own purposes. The programs are characterized by a fairly limited set of alternatives, based on the program purposes and the mechanisms used to alleviate drought impacts. Program purposes fall into some combination of efforts to reduce the quantities of water used, develop new sources of supply, recycle water for reuse, or provide financial support to enterprises suffering drought damage and thereby assist in their recovery. For the most part, mitigation programs are government efforts to influence water users, although local governments in particular may construct facilities on their own initiative. The principal mechanisms used to lessen drought impacts are 1) information programs to increase awareness of the drought, encourage conservation, and describe ways of saving water; 2) price changes to make high volume uses less economical; 3) taxes, grants, and loans to encourage specific activities (water system leakage repair, well-drilling), discourage "wasteful" activities, or assist in recovering from drought damage; 4) administrative allocations such as rationing programs and exchange arrangements; and 5) other regulations (new hook-up restrictions, plumbing code changes).

There is a tendency to evaluate program effectiveness in terms of the achievement of program goals. Ideally, evaluation should balance program accomplishments against the costs of achieving them, since achieving program goals may cost more than is warranted by the results. Practically, however, it is difficult to compare money spent on drought relief with the benefits achieved. The benefits are widely dispersed and often difficult to measure.

Estimation is further complicated from a national economic efficiency perspective because of distortions produced by taxing people with sufficient water to subsidize drought victims. From a local perspective, most drought program money is often capital used to increase water supplies during future shortages whose magnitudes and timing are difficult to predict in even a probabilistic sense. Undoubtedly, the difficulty of measuring the net benefits from drought relief

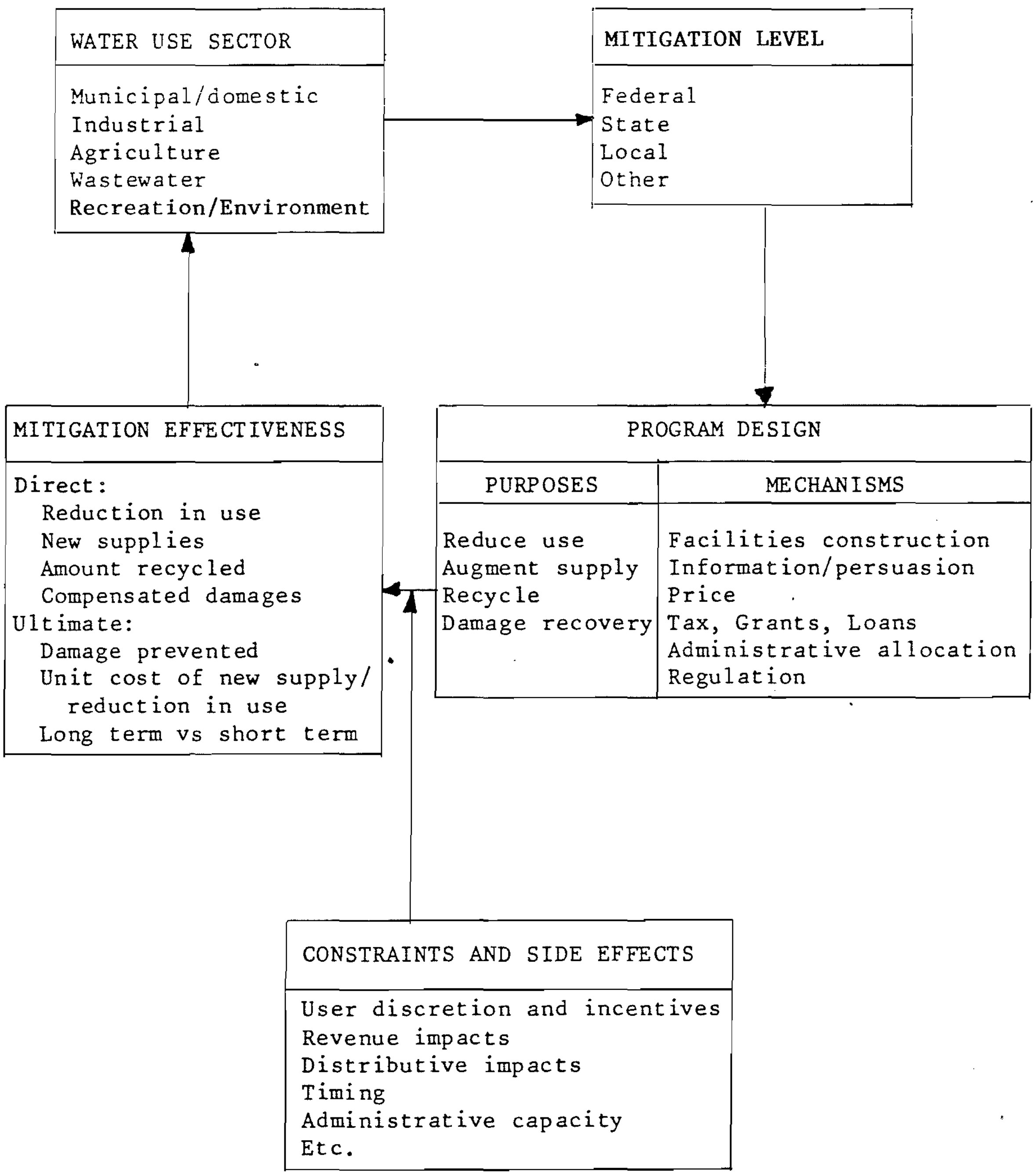

Figure 1. Drought impact mitigation program cycle.

programs is a strong reason for so few evaluations.

One format for organizing drought experiences is through a tabular display structured according to the schematic of Figure 1. Water use sectors provide the primary divisions and can be subdivided by the government level initiating the program. Entries are made by purpose and mechanism, constraints and side effects, and effectiveness, and then cited by a source citation. Such a tabular display of information on the 1976-77 drought is given in the Appendix.

An Analysis of Drought Policy Effectiveness in the Municipal Sector

Introduction

Many municipal water supply systems in Utah (particularly the larger urban systems) depend largely upon surface water sources. In 1976-77, the below-normal precipitation during the winter and the resulting low spring runoff adversely affected surface water availability. Because of time and financial constraints, the options for augmenting supplies by developing groundwater or constructing facilities for importing water from other areas were not feasible. Lack of large storage facilities and the concern that the drought might continue into the next year prompted municipalities to ration available supplies.

Decisions as to whether to impose rationing mechanisms and the form and the extent to which to impose them depended largely on the municipality's perception of the drought severity as well as its perception of the suitability and effectiveness of the various rationing devices for the specific system. Three major categories of policies for restricting water use, with several variants of each category, were implemented in different parts of the state (Hughes et al. 1978). These were higher prices, mandatory maximum use restrictions, and restrictions on times of outdoor watering. The purpose of this chapter is to evaluate the effectiveness of these various policies in reducing water use in the short run.

Description of Drought Policies

Among the three major rationing policies implemented during the drought period in Utah, the most common was the restriction of watering time for outdoor use. Of the 33 systems for which information was available, 24 imposed time restrictions. Total hours allowed for outdoor watering in a week ranged between 0 and 105 hours. Nine systems implemented price changes, and five systems imposed mandatory quantity restrictions. There were three systems that had price changes as well as time restrictions. Four systems had both time restrictions and mandatory quantity restrictions. Price increases ranged from $0.03 to $1.25 per 1000 gallons (10 percent to 500 percent). The quantity restrictions ranged from 36,000 gallons per connection to 6000 gallons per connection per month. The distributions of normal (average for years 1973-75) water use per capita and per connection for the 33 communities are shown in Figures 2 and 3. The water use reductions achieved during the drought are shown in Figure 4. The mean reduction was 156 gallons per connection. The standard deviation was 214. Although 27 systems reported a reduction in water use, six systems had an increase. This study attempts to quantify the water use reductions associated with different policies and thereby establish the relative effectiveness of each of the rationing devices through a cross-sectional analysis using a multiple regression model. To formulate an appropriate model, it is important to understand the mechanisms whereby the different policies affected water use.

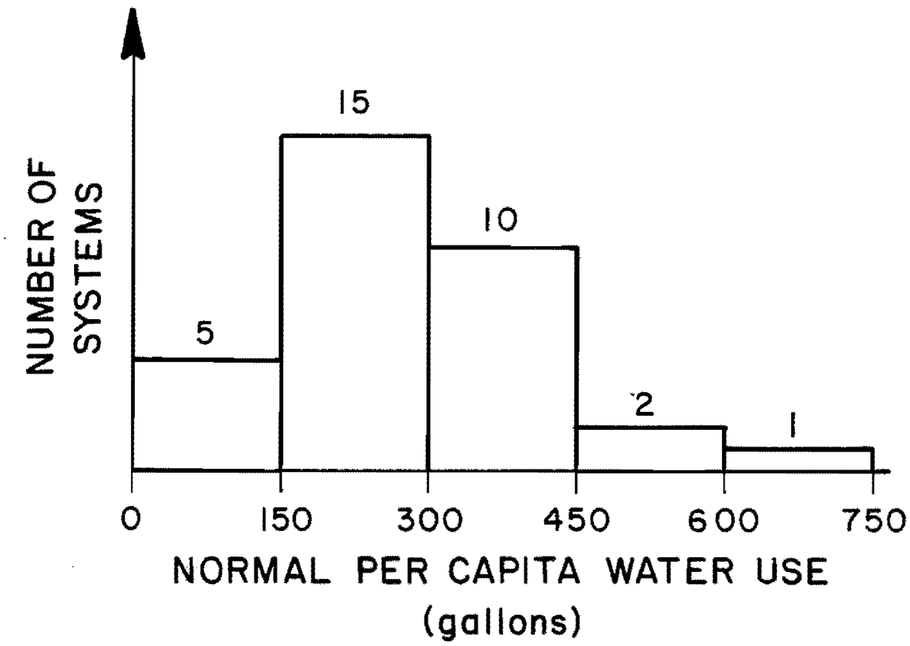

Figure 2. Normal water use per person.

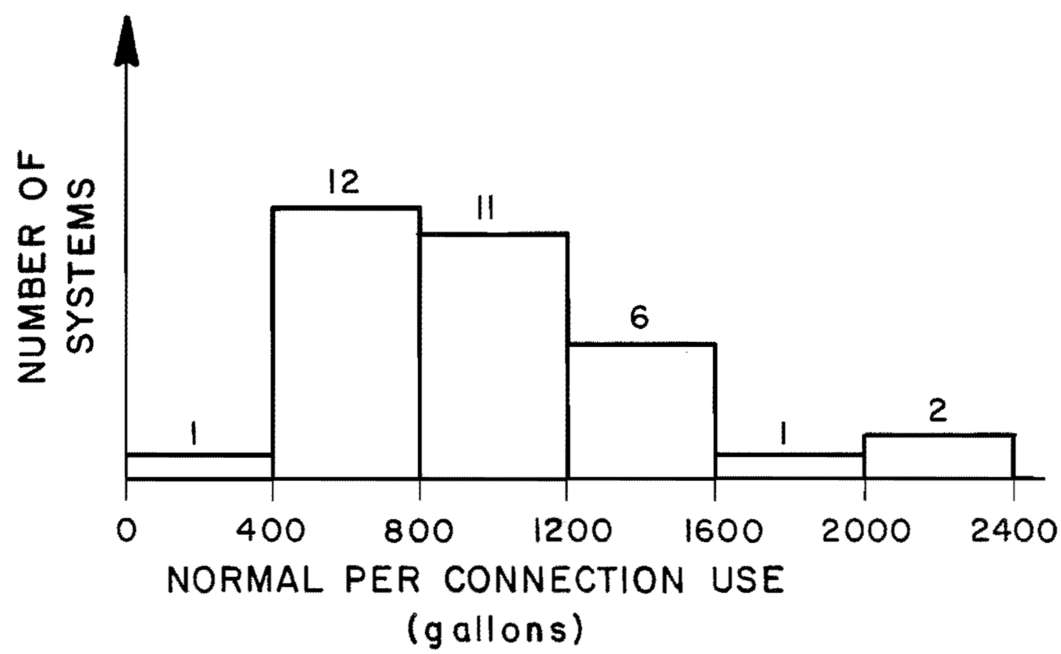

Figure 3. Normal water use per connection.

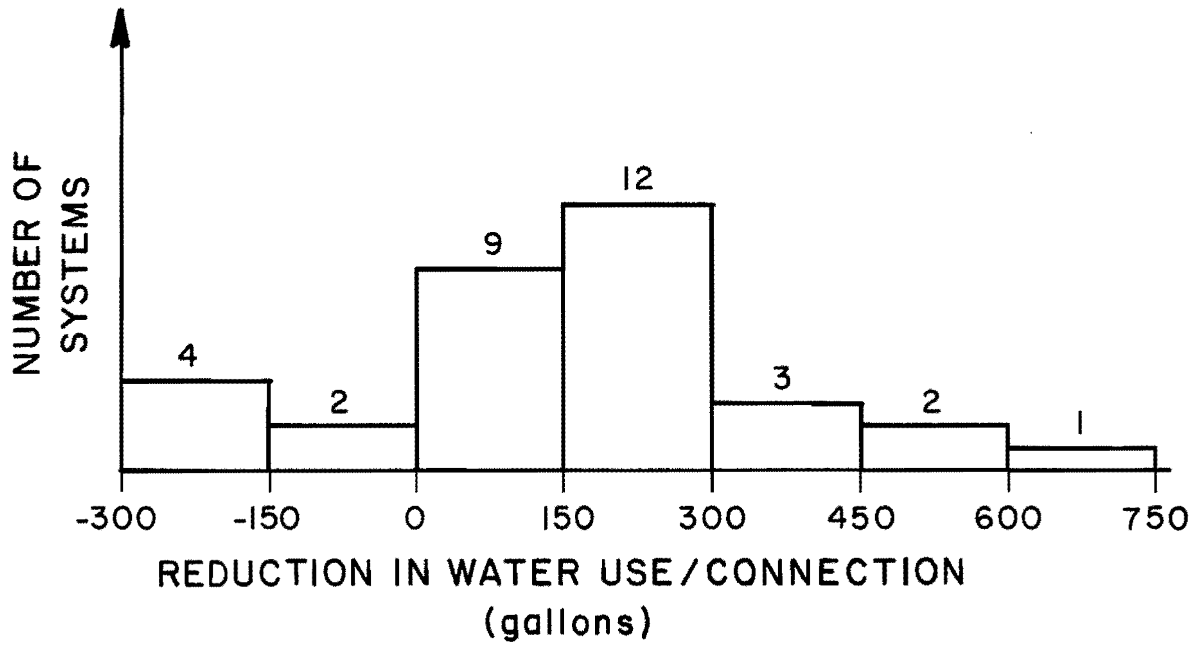

Figure 4. Water use reductions.

Changes in Prices

The price structure for most of the municipalities included a fixed monthly charge for a connection. This monthly charge allowed the users to consume up to a specified number of gallons with no additional charge. The minimum monthly charge varied from $2 to $11, and the quantity allowance varied from 3,000 to 12,000 gallons. In addition, there was a price for water consumption in excess of the allowance. Generally, the additional price ranged from $0.10 to $0.30 per thousand gallons. Some of the systems reported increasing multiple block rate structures and a couple of systems had declining multiple block rate structures. Two systems had a flat rate per connection with no variable charges based on the quantity of water consumed.

Price changes during drought included a) an increase in the minimum charge (either directly or by decreasing the quantity that could be used without increasing the charge), b) an increase in the price associated with additional water consumption, and c) an increase in the progressivity of the multiple block rates.

The three cases are illustrated in Figure 5. In Figure 5a, D represents the demand for water. When the minimum charge is raised or the quantity entitlement corresponding to this minimum charge is reduced (from Q^* to $Q^{*\prime}$), the demand D will shift to D' due to an income effect (normally small) causing a change in quantity consumed from Q to Q'. In Figure 5b, the price is changed from P to P'. In Figure 5c, the demand curves for two users, D_1 and D_2, are shown each facing a different price P_1 and P_2 respectively. When their prices are increased to P_1' and P_2', their quantity demanded falls from Q_1 and Q_2 to Q_1' and Q_2' respectively.

In case (a), the cost of the intramarginal units increases with no change in the price of the marginal units. If the income effects are small, such changes will have negligible effect on water consumption. In case (b), the

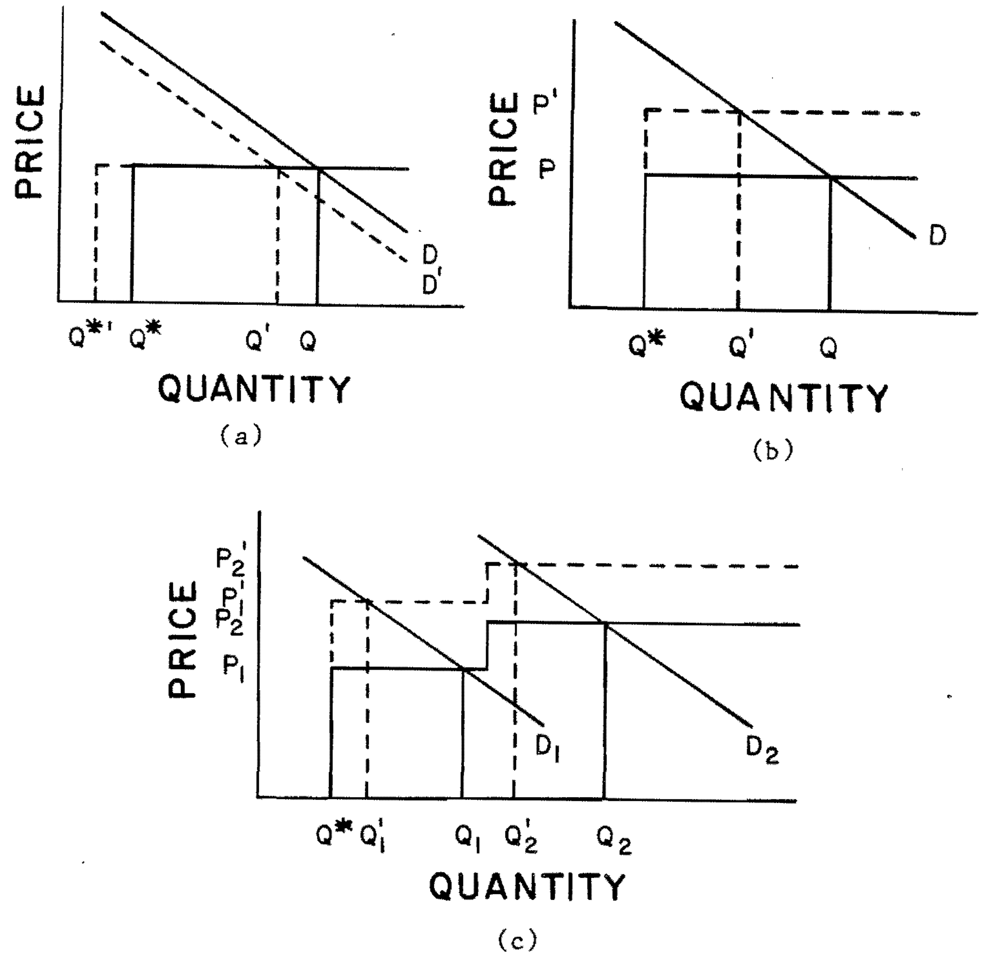

Figure 5. Effect of price changes on water use.

quantity consumed will change by an amount determined by the price elasticity of demand for water and the change in the price. In case (c), the costs of both the intramarginal units as well as the marginal units will increase. As under the assumption that the income elasticity of demand for water is small, the effect on marginal units can be calculated as for case (b). However, there are additional complications in measuring price changes in this case due to the multiple block rates. The price changes for each block could be different. In order to measure the effective price change, one must know the demand distribution. Since such information was not available to this study, the price change corresponding to the average consumption block was taken to represent the effective price change.

Time Restrictions

The most common type of time restriction imposed on outdoor water use was to allow a household to water only on particular days. Usually the restrictions specified the hours for lawn watering, presumably to maintain adequate pressure for fire hydrants. The total hours in a week during which water use was restricted ranged from 4 to 83 in the sample. Many systems imposed the time restrictions on a voluntary basis. Some cities, however, passed an ordinance prohibiting water use for certain times, thus making the restrictions mandatory. Because no special enforcement effort was made in the mandatory cases, no attempt was made to distinguish between the voluntary and mandatory restrictions in the analysis. The total hours of restrictions were computed for each of the systems in the sample.

The effect of time restrictions on outdoor use could be analyzed as follows. A household can be assumed to produce "lawn and garden" output by combining water, labor and other purchased inputs. The optimal amount of "lawn and garden" is determined by the intersection of the demand and the supply curves. The supply is the marginal cost of producing an additional unit area of "lawn and garden" where water and household labor are inputs. The time restrictions influence the opportunity cost of household labor by shifting the individual's time schedule for watering. In the absence of mechanical devices for watering (such as timers, automatic lawn sprinklers, etc.), the changes required in the time schedule of the homeowner impose additional costs on his time. Under "moderate" time restrictions, this factor (increased opportunity cost of his time) may predominate causing the derived demand for outdoor water use to shift downward. Under more "stringent" time restrictions, the amount of water deliverable to lawn and garden may be severely limited, implying a quantity rationing of outdoor water use.

These concepts are illustrated in Figure 6. In Figure 6a, the demand D and marginal cost S curves for "lawns and gardens" are shown. The normal area for lawn and garden A_o is determined by the intersection of D and S. The demand curve for water D_w for this area is shown in Figure 6b as derived from given prices for all inputs such as households, time cost, fertilizer, etc. At the initial price P_w, an amount Q_o is used outdoors. When a time restriction is imposed, the opportunity cost of labor increases causing the demand for water D_w to shift to D_w' assuming water and labor inputs are complementary. This will cause the supply of lawn and garden to shift from S to S'. The new quantity A_o' of lawn and garden is irrigated with q_o'. A reduction of q_o to q_o' is achieved through this policy. However, with "stringent" time reductions, the individual may not be able to use the amount of water he desires. This situation is also shown in Figure 6b where the demand shifts to D_w''. The desired quantity at price P_w is q_o''. However, the amount of water that the user is able to withdraw from the system is q_o^* (within the given time). The shadow price of water is P_w^* under this scheme for rationing outdoor water use.

While restrictions limiting the times of watering may not affect all the households served from a given system, the number of connections affected will increase with the hours of restriction. Reasons for differential effects among households include different lot sizes, the shadow prices of labor for gardening, and the number of people in the household. The effect on aggregate demand can be illustrated with the aid of Figure 7. Let D_1 and D_2 represent two household demands, and let D be the aggregate demand curve. A time restriction will shift D_1 and D_2 downward and hence the aggregate demand D downward to D'. A "severe" time restriction might impose quantity rationing on individual 2 but not individual 1. In this case individual 2 can consume only up to q_2^* while consumption by individual 1 is determined by his demand curve. The aggregate demand D is further reduced to D". As the time restriction becomes more severe, a greater shift in the aggregate demand can be expected as more households become affected.

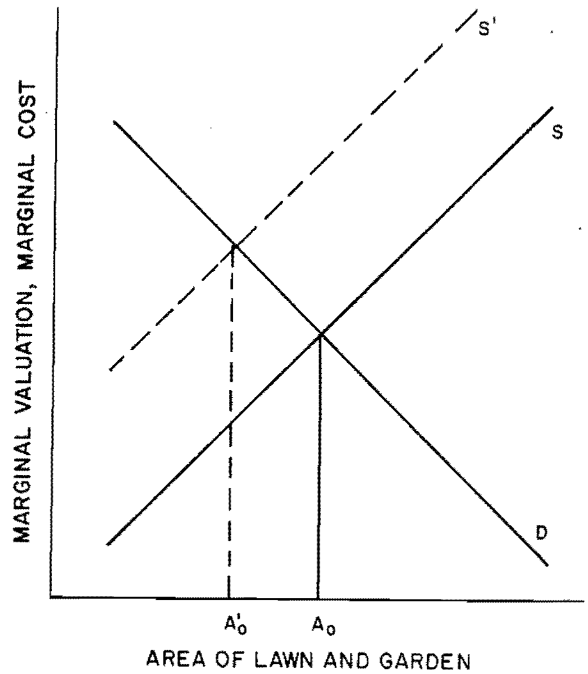

Figure 6a. Demand and supply for lawn and garden.

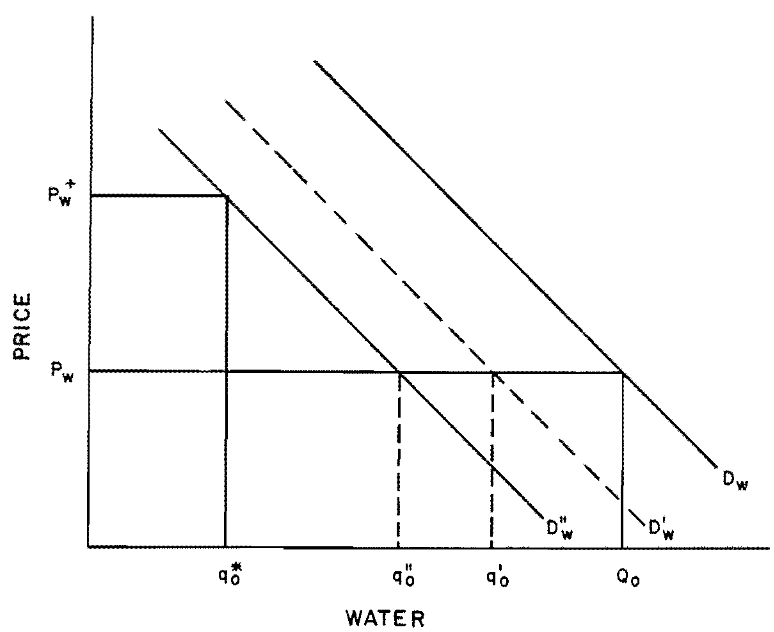

Figure 6b. Effect of time restrictions on outdoor water use.

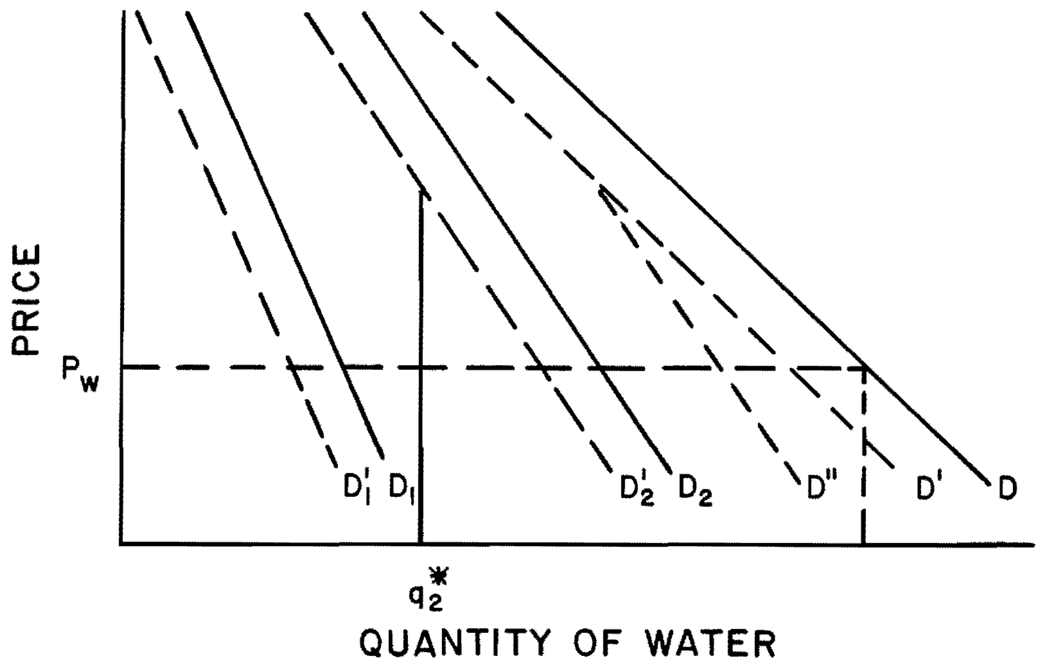

Figure 7. Effect of restricting watering time on aggregate demand.

Mandatory Maximum Use Restrictions

According to this policy for restricting water use, the maximum amount of water that can be consumed per month per connection is limited to a specified quantity. The restrictions per connection ranged from 6,000 gallons to 36,000 gallons per month. Unlike time restrictions where only the outdoor water use is affected, the quantity restriction affects both indoor and outdoor uses. However, the restriction allows the household to allocate water between indoor and outdoor use in any manner it chooses, while the time restriction distorts this allocation by restricting only the outdoor use.

Quantity rationing does not affect households that would use less than the rationed amount anyway. As the ration is reduced, more households are constrained. The economic relationships through which this scheme affects aggregate demand are similar to those for "stringent" time restrictions in that aggregate demand shifts to the left as in Figure 7. However, this shift has to be distinguished from time restrictions in that it reduces both indoor and outdoor uses whereas for time restrictions, although the total water use might decrease, the indoor use actually might increase.

An index was constructed to measure the quantity restriction. The need for an index, instead of using the ration quantity directly, arises due to systems that did not have quantity rations. For these systems, a zero value could not be used since it would cause numeric difficulties. The maximum average monthly use per connection was found to be approximately 60,000 gallons. This figure was used as a restriction for systems that did not use any quantity rationing. The index Q was defined as the ratio of the ration amount to 60,000. This measure is 1 for systems that did not impose rations and between 0 and 1 for those that did. The index falls as the ration quantity decreases.

Other Restrictions

In addition to the above three policies, many of the water supply systems implemented other water use restrictions. These included prohibition of water use for washing parking lots, driveways, and sidewalks, and reductions of water use in city parks. Quantitative measures of such restrictions were not available, and their effects were ignored in the analysis.

Model Formulation

An empirical model is needed to evaluate how various drought policies affected water use. The logical starting point is to assume a household demand function. Several demand studies (Howe and Linaweaver 1967, Gardner and Schick 1964, Hansen and Narayanan 1981, Hanke 1970, Young 1973, Hughes 1980) suggest relevant variables as important in the determination of water demand. For example, one might use a general demand relationship of the form:

$$X = X(P, I, N, L, R_f, T) \quad . \quad . \quad . \quad . \quad (1)$$

where X is the consumption of water per connection, P is the marginal price, I is the household income, N is the number of people in the household, L is the lot size, R_f is the rainfall and T is the temperature during the growing season. In this formulation, the water demand is determined by household characteristics L and N, environmental variables R_f and T, and economic variables P and I. The drought policy variables then need to be introduced. These are the time restriction R, the quantity restriction Q, and the changed price. Now, the demand X can be written as

$$X = X(P, R, Q, I, N, L, R_f, T) \quad . \quad . \quad (2)$$

Since the purpose of the study is to evaluate drought policies and not to estimate the demand, one can consider the total derivative of the above demand,

$$dx = \frac{\partial x}{\partial P} dP + \frac{\partial x}{\partial R} dR + \frac{\partial x}{\partial Q} dQ + \frac{\partial x}{\partial I} dI + \frac{\partial x}{\partial N} dN + \frac{\partial x}{\partial L} dL + \frac{\partial x}{\partial R_f} dR_f + \frac{\partial x}{\partial T} dT \quad . \quad (3)$$

In the above expression, it can be assumed that no changes in I, N, L, and T are caused by drought conditions. The changes in the other variables were taken as their differences between a predrought period defined as the average during 1973-1975 and the drought period taken as the 1977 calendar year. The rainfall was included in the model for the 1977 growing season as an explanatory variable because the average summer rainfall for most sites in Utah in 1977 was larger than normal (water supply primarily comes from winter snow) and could have reduced water use. The change in use per connection is thus given by

$$dx = \frac{\partial x}{\partial P} dP + \frac{\partial x}{\partial R} dR + \frac{\partial x}{\partial Q} dQ + \frac{\partial x}{\partial R_f} dR_f \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

For small changes, assuming the respective derivatives to remain constant, a linear model with the stochastic specification can be given by

$$X_0 - X_1 = \alpha_P(P_1 - P_0) + \alpha_R R + \alpha_Q(1 - Q) + \alpha_{R_f}(R_{f_0} - R_{f_1}) + \varepsilon \quad . \quad (5)$$

where ε is assumed to be random disturbance term with zero mean and constant variance. Equation 4 can also be written in percentage form as

$$\frac{dx}{x} = \alpha'_P \frac{dP}{P} + \alpha'_R \frac{dR}{R} + \alpha'_Q \frac{dQ}{Q} + \alpha'_{R_f} \frac{dR_f}{R_f} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The coefficients α_P', α_R', α_Q' and α_{R_f}' represent elasticities or percentage changes in per connection consumption per unit percentage change in the explanatory variables P, R, Q, and R_f.

Equation 6 can also be given a stochastic specification like Equation 5

$$\frac{X_0 - X_1}{X_0} = \alpha'_P \frac{(P_1 - P_0)}{P_0} + \alpha'_R \frac{R}{168} +$$

$$\alpha'_Q \frac{(1 - Q)}{1} + \alpha_{R_f} \frac{(R_{f_0} - R_{f_1})}{R_{f_0}} + \varepsilon \quad . \quad (7)$$

where the base values for R and Q are respectively 168 (total hours in a week) and 1 (systems with no ration quantity).

The procedure followed in assessing the impacts of the drought measures with these equations follows immediately below. Numerical results are given in the next section. First Equations 5 and 6 were estimated using ordinary least squares for preliminary evaluation of the model. The linear form appeared to provide better explanatory power than the percentage form. Therefore, the linear form was retained for further analysis.

The assumption that the coefficients (αs) are constant may be somewhat restrictive. For the time restriction, α_R is likely to be related to the average normal consumption per connection X_0 and the number of people in a household N. With the same N, the larger the value of X_0, the greater will be the effect of time restriction. Similarly, given the same X_0, for any two systems, the system with larger N is likely to experience a smaller effect on water use than is the system with smaller N. Therefore, it is hypothesized that

$$\alpha_R = \alpha_{R_0} + \alpha_{R_1} X_0 + \alpha_{R_2} N \quad . \; . \; . \; .. \quad (8)$$

Substituting this relationship, Equation 5 becomes

$$X_0 - X_1 = \alpha_P (P_1 - P_0) + \alpha_{R_0} R + \alpha_{R_1} X_0 R$$

$$+ \alpha_{R_2} NR + \alpha_Q (1 - Q) + \alpha_{R_f} (R_{f_0} - R_{f_1}) + \varepsilon$$

$$. \; . \; . \; . \; . \; . \; . \; . \quad (9)$$

The regression results showed the explanatory power of the equation to improve greatly, and the coefficients had the expected signs.

The other coefficients in Equation 5 were also tested to see if they depended on X_0 and N. In particular, the following relationships were postulated:

$$\alpha_Q = \alpha_{Q_0} + \alpha_{Q_1} X_0 + \alpha_{Q_2} N \quad . \; . \; . \; . \; . \quad (10)$$

and

$$\alpha_P = \alpha_{P_0} + \alpha_{P_1} X_0 + \alpha_{P_2} N \quad . \; . \; . \; . \; . \quad (11)$$

These relationships were substituted in Equation 9 one at a time. The criteria used to judge the explanatory power of the added variables included $\bar{R}^2$ (the value of R^2 adjusted for the degrees of freedom) and the t values for individual coefficients. In both cases, the value of $\bar{R}$ declined from that with Equation 9, and the t statistics for the three coefficients of Equations 10 and 11 were not significantly different from zero at 10 percent level. In fact, only one t value corresponding to the estimate of α_{P_1} was greater than 1. The F statistic was also lower in both cases compared to Equation 9. Based on this analysis, it was concluded that α_Q and α_P can be regarded as constants.

Of the 24 systems which had time restrictions, 9 were voluntary. While the other 15 systems made little enforcement effort, they may have achieved better compliance because of an expectation of possible penalty costs. To examine for significant differences between these two groups, a test of the hypothesis that the water use reduction for the voluntary case is different from that for the mandatory case was proposed. To do this, Equation 8 was rewritten as

$$\alpha_R = \alpha_{R_0} + \alpha_{RD}D + \alpha_{R_1}Q + \alpha_{R_2}N \quad . \quad . \quad (12)$$

where D = 1 if voluntary restriction was imposed and 0 otherwise. The null hypothesis could not be rejected if α_{RD} turned out to be significantly different from zero. After substituting Equation 12 into Equation 9, the following equation was reestimated:

$$X_0 - X_1 = \alpha_P \ (P_1 - P_0) + \alpha_{R_0} R + \alpha_{RD}D + \alpha_{R_1} X_0 R + \alpha_{R_2} NR + \alpha_Q \ (1 - Q) + \alpha_{R_f} (R_{f_0} - R_{f_1}) + \varepsilon \quad . \quad . \quad . \quad . \quad (13)$$

The α_{RD} estimate proved significant at the 5 percent level, and the values of $\bar{R}$, R^2, and t indicated that the coefficients were significantly different from 0 at the 5 percent level. The numerical results of the estimated equations (Equations 5, 6, 9, and 13) and their implications are discussed below.

Model Results

A statewide water use survey was made in Utah near the end of 1977 jointly by the Utah Water Research Laboratory and the Utah League of Cities and Towns. A section of the survey instrument related specifically to the drought was included (Hansen et al. 1978). Data from 33 cities were sufficiently complete to be used in the regression model. Table 1 contains these data. The models in linear and percentage forms corresponding to Equations 5 and 6 were estimated by ordinary least squares. The estimated equation and the associated statistics were:

Model A:

$$(X_0 - X_1) = 281.7 \ (P_1 - P_0) + 0.598 \ R + 283.2 \ (1-Q) - 57.3 \ (R_{f_0} - R_{f_1}) \quad . \quad . \quad . \quad (14)$$

t values: (1.790)(1.744)(1.723)(-1.833)

$R^2 = 0.47 \quad \bar{R} = 0.40 \quad F(4,29) = 6.53$

Model B:

$$\left(\frac{X_0 - X_1}{X_0}\right) = 0.088 \frac{(P_1 - P_0)}{P_0} + 0.0866 \left(\frac{R}{168}\right) + 0.541 \ \frac{(1-Q)}{I} - 0.107 \frac{(R_{f_0} - R_{f_1})}{R_{f_0}} \quad . \quad . \quad . \quad (15)$$

t values: (2.314)(1.510)(3.330)(-0.993)

$R^2 = 0.54 \quad \bar{R} = 0.48 \quad F(4,29) = 8.51$

In Equation 14, all the individual coefficients are significantly different from zero at the 5 percent level, and the F ratio indicates that the set of coefficients as a whole is significantly different for zero at the 5 percent level. In Equation 15, the estimated coefficient of α_{R_f} has a low + value and the estimated coefficient of α_R is significantly different from zero at only 10 percent level.

The results of the two models can be compared at the mean values of the explanatory variables. By taking the reference value of price $\bar{P}$ = 0.25/1000 gallons, water use $\bar{X}_0$ = 1000 gallons per connection per day, rainfall $\bar{R}_f$ = 3.5 inches, time restriction $\bar{R}$ = 125 hours and the quantity restriction $\bar{Q}$ = 0.5 (30,000 gallons per month), the coefficients of Models A and B are converted to examine changes in water use reduction.

Table 1. Regression model data.

System Name	County	Population 1973-75	Population 1977	Number of Connections 1973-75	Number of Connections 1977	Water Use Million gallons/year 1973-75	Water Use Million gallons/year 1977
Aurora	Sevier	613	785	189	242	33	60
Fillmore	Millard	1,736	2,726	724	913	284	297
Heber	Wasatch	3,535	3,448	1,233	1,230	554	416
Ivins	Washington	203	331	96	157	28	34
Kearns	Salt Lake	13,473	15,092	3,849	4,312	1,267	693
Layton	Davis	17,708	19,678	4,184	4,412	1,227	1,076
Lehi	Utah	5,688	7,015	1,658	1,852	386	355
Lindon	Utah	2,030	2,514	457	550	153	183
Manilla	Daggett	319	375	184	247	28	48
Pleasant Grove	Utah	6,186	9,077	1,868	2,254	765	1,174
Provo	Utah	59,000	67,744	10,639	11,218	6,331	6,401
Riverton	Salt Lake	4,900	6,192	1,232	1,548	288	244
Salt Lake Co.WCD	Salt Lake	17,920	19,950	5,973	6,650	1,792	1,466
So. Davis WID	Davis	5,171	6,219	1,620	1,762	246	247
So. Jordan	Salt Lake	3,823	5,009	886	1,165	238	214
So. Salt Lake	Salt Lake	8,748	9,197	2,640	2,705	931	1,012
Spanish Fork	Utah	8,779	9,309	2,545	2,756	681	899
Springville	Utah	9,887	10,816	2,933	3,209	2,237	1,728
Taylor-Bennion	Salt Lake	16,678	25,452	4,768	7,272	1,276	1,267
Uintah	Uinta	521	712	149	203	61	64
Vernal	Uinta	12,563	12,472	3,315	3,043	1,543	1,380
Washington Terrace	Weber	7,909	8,540	1,911	2,005	278	283
Brigham City	Box Elder	15,367	16,400	3,904	3,964	2,207	1,777
East Carbon	Carbon	2,100	2,200	671	747	273	161
Hyrum	Cache	2,955	3,485	946	1,100	524	499
Jensen WID	Uintah	571	820	143	205	32	37
Kenilworth	Carbon	503	509	108	109	19	9
Monticello	San Juan	1,692	1,900	578	650	195	96
North Salt Lake	Davis	2,781	3,573	624	812	480	685
Orem	Utah	33,801	42,678	7,898	10,042	3,605	3,647
Payson	Utah	6,368	8,200	2,000	2,300	1,028	1,000
Price	Carbon	10,564	11,193	4,056	4,332	989	834
West Bountiful	Davis	1,945	2,500	386	615	89	99

Table 1. Continued.

System Name	Change in Water Use (gal/day/conn.)	Price Change ($/1000 gal)	Percent Price Change	Voluntary Time Restriction (hr/wk)	Mandatory Time Restriction (hr/wk)	Mandatory Quantity Restriction Index (1-Q)	Change in Rainfall (inches)	Percent Change in Rainfall
Aurora	-200	0	0	0	133	0	-0.24	-0.085
Fillmore	184	0	0	0	0	0	0.56	0.166
Heber	303	0	0	0	147	0	-0.43	-0.112
Ivins	199	0.25	83	0	0	0	-0.46	-0.239
Kearns	461	0	0	0	164	0.67	-0.76	-0.210
Layton	135	0.15	60	0	0	0	0.10	0.024
Lehi	112	0.10	50	0	0	0	-1.01	-0.334
Lindon	10		0	96	0	0	0.16	0.049
Manilla	-109	0.05	10	0	0	0	-0.68	-0.178
Pleasant Grove	-303		0	156	0	0	-1.01	-0.334
Provo	67		0	0	144	0	-1.01	-0.334
Riverton	209		0	0	164	2.0	-0.76	-0.210
Salt Lake Co. WCD	217		0	0	164	0.67	-0.76	-0.210
So. Davis WID	31		0	0	163	0	0.10	0.024
So. Jordan	233		0	0	164	0.67	-0.76	-0.210
So. Salt Lake	-58		0	164	0	0	-0.76	-0.210
Spanish Fork	-160		0	0	0	0	0.16	0.049
Springville	614		0	0	156	0	-1.01	-0.334
Taylor-Bennion	255		0	0	164	0	-0.76	-0.210
Uintah	271	0.08	36	0	0	0	-0.74	-0.261
Vernal	33	0.40	200	160	0	0	-0.74	-0.261
Washington Terrace	12		0	0	158	0	-0.35	-0.081
Brigham City	320	0.03	16	0	0	0	-4.80	-1.411
East Carbon	523		0	0	168	0	0.19	0.046
Hyrum	276		0	0	84	0	-3.82	-0.972
Jensen WID	127		0	132	0	0	-0.74	-0.261
Kenilworth	269		0	0	0	9.0	0.19	0.046
Monticello	523	1.25	500	168	0	0	-0.83	-0.149
North Salt Lake	-200		0	84	0	0	0.10	0.024
Orem	255		0	63	0	0	-1.01	-0.334
Payson	217		0	84	0	0	0.16	0.049
Price	140		0	0	144	0	0.19	0.046
West Bountiful	190	0.27	117	0	164	0	0.10	0.024

The results suggest that at these reference values, a 1 percent increase in price will reduce water use by 0.07 to 0.09 percent. A 1 percent increase in time restriction (1.68 hours per week) reduces water use by 0.064 to 0.075 percent. A 1 percent increase in Q (implying a restriction of an additional 3,000 gallons/month from the initial 30,000 gallons) will lead to a 0.014 to 0.054 percent reduction in water use. If the rainfall during the growing season exceeds the mean value by 1 percent, a reduction of 0.1 to 0.2 percent in water use would take place. The corresponding water use reductions in gallons per day per connection are shown in parentheses in Table 2.

Due to the lower t values in Model B for some of the coefficients, Model A was used as the basis for further analysis. Equation 9 was estimated using ordinary least-squares. The result was

Model C

$$X_0 - X_1 = 232.5(P_1 - P_0) + 2.57\,R - 0.84\,NR + 0.00122\,X_{0R} + 335.71(1-Q) - 50(R_{f_0} - R_{f_1}) \quad . \quad . \quad . \quad . \quad (16)$$

t values: 1.591 1.754 -2.254 1.899

2.201 -1.726

$R^2 = 0.59 \quad \bar{R} = 0.5 \quad F(6,27) = 6.47$

Except for the price change, all the coefficients are significant at the 5 percent level. The price change coefficient is significant at the 10 percent level. The F ratio and the R^2 and $\bar{R}$ values improved significantly. The price elasticity decreased at the reference values. The mandatory quantity restriction and the rainfall variable have more pronounced effects on water use. The effectiveness of time restriction is now a function of X_0 and N. At a reference value for N = 3.5 and X_0 = 1000, the coefficient of R is 0.85 as compared to 0.598 for Model A.

The hypothesis, that the water use reductions in the case of voluntary time restriction was significantly different from that with the mandatory restriction, was tested based on Equation 13. The estimated equation and the associated statistics are provided below:

Model D

$$X_0 - X_1 = 412.1(P_1 - P_0) + 2.24\,R - 1.69\,D_R - 0.707\,NR + 0.0015\,X_0R + 267.7\,(1-Q) - 48\left(\frac{R_{f_0} - R_{f_1}}{R_{f_0}}\right) \quad . \quad (17)$$

Table 2. Comparison of water use for Models A and B.

Coefficients	Reference Values	Model A Percent	(gal/day)	Model B Percent	(gal/day)
α_P'	$\bar{P}$ = 0.25	0.07	(70)	0.088	(88)
α_R'	$\bar{R}$ = 125	0.075	(75)	0.0644	(64.4)
α_Q'	$\bar{Q}$ = 0.5	0.014	(14.2)	0.054	(54)
α_{R_f}'	$\bar{R}_f$ = 3.5	-0.200	(200)	-0.107	(107)

t values: 2.857 1.712 -2.86 -2.1

2.586 1.945 -1.868

$R^2 = 0.69$ $\bar{R} = 0.6$ $F(7,26) = 8.19$

The coefficients are all significantly different from zero at the 5 percent level. The F ratio also indicates that the set of coefficients is significantly different from zero. The value of $\bar{R}$ and R^2 increased from the previous model. Based on the t value corresponding to D_R, the hypothesis could not be rejected. The coefficient of D_R has the expected sign.

Model D suggests a price elasticity of 0.103 at the base values of P = \$0.25/1000 gallon and X_0 = 1000 gallons per day. The coefficient of time restriction at the reference values is given by 1.27 for mandatory restriction and -0.58 for voluntary restriction. This implies that an average hour of time restriction per week reduces water use by 1.27 gallons per day if mandatory and increases water use by 0.58 gallons per day if voluntary. Although voluntary restriction increases use at the base values of X_0 and N, systems with large values of X_0 and small values of N (large initial use and small families) would experience use reductions with voluntary restrictions. In fact, only three of the nine systems that had voluntary restriction actually experienced increased consumption. One possible explanation for this effect is that voluntary restriction may cause the consumer to expect more stringent restrictions later in the season and respond by overwatering. In any case, voluntary restriction does not seem to be an effective tool in reducing water use.

Conclusions

A multiple regression model was developed to determine the water use reductions achieved by three efforts of communities to conserve water. These efforts were price increases, time restrictions on the hours of outdoor water use, and volume restrictions on maximum monthly water use. According to the best model:

1. A 1 percent increase in price leads to one tenth of a percent decrease in the quantity consumed.

2. The effectiveness of time restrictions on outdoor use depends upon the "normal" water use level, the number of people in the household, and whether or not the restriction was imposed on a voluntary or mandatory basis. An increase in the mandatory time restriction of 1 hour per week decreases total water use by 1.27 gallons per day if the average water use is 1000 gallons per day for an average connection serving 3.5 people. For systems with higher use levels and fewer people per connection, the water use reduction will be greater. For the case of voluntary restriction, water use sometimes increased, particularly for systems with smaller use levels and higher number of people per connection.

3. For every 1000 gallon reduction in maximum monthly water use, a reduction of 4.46 gallons per day in use was observed.

From an economic efficiency point of view, mandatory restrictions on the times of outdoor watering are a poor choice of policy because they affect only one type of use. Unless enforcement costs are significantly higher or fewer marginal uses occur indoors, mandatory quantity restrictions are better since they allow households to allocate water between outdoor and indoor uses in any way they choose. They do not distort the marginal rate of substitution between indoor and outdoor water uses.

If distributional considerations are not important, the third method, price change, would be a still better alternative since the marginal rate of substitution between water and all other goods used by households would remain equal. However, from the model, it appears that the short-run price elasticity is small and it might take a large increase in price to accomplish a reasonable reduction in use. A 20 percent reduction in water use would require more than doubling the price.

Voluntary periods for outdoor watering was ineffective in reducing water use. On the other hand, there was little cost; and the program may be a reasonable alternative for areas with high use levels and few users per connection.

CHAPTER III

USE OF RATIONING IN THE MANAGEMENT OF RESIDENTIAL WATER SYSTEMS WITH A STOCHASTIC SUPPLY

Introduction

Many of the municipal water supply systems in the western United States depend largely upon surface water sources which exhibit substantial annual variability. Such communities are often reluctant to vary the price of water as a means of coping with supply variability. This may be due to lags in the bureaucratic process required for price determination, desire for price stability, or concern for equity. Perhaps the National Water Commission (1973, p. 251) was considering these factors when it recommended:

> (Water) Users should ... be reasonably certain as to the pricing situation they face. This means that ... overall price structure should not be changed frequently. ... The uncertainty to be avoided is frequent or abrupt changes--more often than every three to five years--in the overall price structure.

However, short-run price rigidity leads to shortages whenever the available water is less than the total quantity demanded at current prices. The traditional mechanism to deal with these shortages is to implement some form of rationing.

If the demand curves for water by each individual were known, the ration allotments could be set to make the marginal values equal to all users at the point where the water supply is exhausted. This would result in the optimal distribution of the water supply but would require complete and perfect information on the water market.

Because this is unrealistic, economists are more likely to recommend taking advantage of the market by issuing resalable ration coupons to water users (Layard and Walters, pp. 200-201). The method eliminates the welfare losses associated with more rigid rationing, but the administrative costs of issuing ration coupons and implementing the transfer of water entitlements from one household to another may be more costly than the welfare gains achieved.

A more common rationing scheme is to set different quotas for different households based upon their past water consumption during normal years. If consumers have advance knowledge that this method of rationing will be implemented at times of water shortage, they would tend to shift their demand functions. That is, they would consume more water when it is plentiful, in order to avoid being penalized during shortages for past low consumption levels.

From an administrative point of view, the least costly method of rationing seems to be to set equal quotas for all users. In this case, there would be no need for information on marginal valuations of water to different users, and the cost of collecting this information would be eliminated. Furthermore, the water users could remain anonymous to the water supply authorities. However, this method of rationing results in unequal marginal rates of substitution for water among users and between water and other goods.

The most common means of enforcing rationing is by imposing penalties on violators. This practice was implemented in California during the drought of 1976-77. In describing the East Bay Municipal Utility District conservation program, Harnet (1978) reports:

> To provide incentive for customers to reduce consumption... excess use charges were established for customers exceeding their allotment. Additional provisions included installation of flow restrictors in meters of domestic customers who persisted in using more than their allotments.... Possible discontinuance of service in cases of continued extreme abuse also was authorized.

Summary of Drought Experience

Many western water utilities were faced with reduced water supplies during the 1976-77 water year. Of the 154 Utah municipal water systems surveyed, approximately 50 percent restricted water usage (Hughes et al. 1978). Half of the restrictions were mandatory and the other half were voluntary. The forms of restrictions included limitations of water use by both days of the week and hours of the day and prohibition of certain outdoor water uses. About 36 percent of the systems increased water prices. However, only a third of these systems admitted to increasing the price due to reduced water supply conditions.

In California, it was estimated that over 150 communities, serving about one-third of all Californians, were subjected to some form of mandatory curtailment of water use during the height of the drought. These mandatory curtailments generally took one of two forms: 1) a percentage reduction from the previous year's use or 2) a quota expressed in gallons per day per person or per household. Nearly all Californians engaged to some degree in water conservation programs (Department of Water Resources/State of California 1978).

The record suggests that, under conditions of water shortage, most water supply authorities prefer to set an equal ration quota for each household. However, the ration allotments are often set arbitrarily, and the long-run water prices are not generally consistent with the rationing scheme imposed during shortages.

Previous Research

A number of researchers have examined the effect of stochastic supplies on water management. Turnovsky (1969) analyzed the effects of stochastic water supply on consumer demand by using supply variation as an argument of the demand function. For water pricing and capacity expansion decisions with stochastic water supply conditions, Crew and Roberts (1970) used maximization of expected welfare gain as the planning criterion. They assume that when there is a water shortage, consumers are ranked according to their willingness to pay, even though they all pay the same price.

There is a large body of literature on rationing electricity when the peak demand exceeds the existing capacity of electric utilities. Brown and Johnson (1969) assumed that capacity could be costlessly allocated among consumers on the basis of greatest willingness to pay. Subsequent authors (Carlton 1977, Crew and Kleindorfer 1978, Meyer 1975, Sherman and Visscher 1978) modified the assumptions about the way capacity is rationed and changed the way that uncertainty enters the demand function. They added new constraints to the problem and derived solutions for an optimal price which is greater than the marginal operating costs (Panzar and Sibley 1978). The common theme of this literature is that the need for rationing stems from the rigid price and stochastic demand experienced by the electric utilities, rather than the stochastic supply serving the relatively stable demand conditions experienced by water utilities and thus the focus of the study. Moreover, the electric utility studies do not address the issue of long run price determination consistent with equal quota rationing.

Theoretical Model: Benefit Function Under Rationing

In this study, economically efficient long run prices (kept rigid in the short run) are derived consistently with quantitative rationing in the context of a stochastic water supply. The derivation follows.

Assume that there are two groups of consumers, with n_1 identical members in the first and n_2 identical members in the second group. Let their individual inverse demand functions be D_1 and D_2, respectively. At long run price(s) (yet unknown), quantities of water demanded by each member of the first and second groups are q_1^* and q_2^*, respectively. Further assume that $q_1^*(P^*) < q_2^*(P^*)$. The total quantity of water demanded is $Q^* = n_1 q_1^* + n_2 q_2^*$.

The available water supply is a random variable represented by Q_s. Let the probability density function of Q_s be $f(Q_s)$. Whenever Q_s falls short of the total demand Q^*, a quota q_r, is set for all consumers.

The following notations are used throughout this study:

- i number of consumer groups $i = 1, 2, \ldots, m$.
- n_i number of consumers in group i.
- n total number of consumers $n = \sum_{i=1}^{n} n_i$.
- D_i identical inverse demand function of each consumer in group i.
- P_i^* optimal long-run price for group i.
- q_i^* quantity of water demanded by each consumer of group i at price P_i^*.
- Q^* total quantity of water demanded $$Q^* = \sum_{i=1}^{m} n_i q_i^*.$$
- $MC(Q)$ marginal cost of supplying water.
- Q_s random variable, available water supply.
- $f(Q_s)$ probability density function of Q_s.
- q_r ration quota for each consumer.
- Q_R total quantity of water demanded at times of rationing.

The higher the price, the less would be the total quantity of water demanded, and the lower would be the probability that the available water supply, which is stochastic, falls short of the total quantity demanded at any given time, and the lower would be the probability of the need for resorting to rationing.

On the other hand, the higher the price of water, the lower would be the total quantity demanded. Therefore, the probability that available water supply will exceed the total quantity of water demanded will be higher. Thus, the probability of foregone consumers' and producers' surpluses will be relatively higher.

In order to balance the two effects and arrive at optimal prices, the procedure is to maximize the sum of the expected producers' and consumers' surpluses. Because of the small share of a typical household budget spent on water, the income effect of a price change for water is neglected. The expected surplus can be defined for a situation where there are two groups of consumers by the sum of Equations 18, 19, and 20 (considering progressively more severe relationships between supply and demand as the supply varies over time) below:

$$\int_0^{(n_1+n_2)q_1^*}\left[n_1\int_0^{q_r}(D_1)dQ + n_2\int_0^{q_r}(D_2)dQ - \int_0^{Q_r}MC(Q)\ dQ\right]f(Q_s)dQ_s \quad . \ . \ . \ . \ . \ . \ . \ . \ (18)$$

$$\int_{(n_1+n_2)q_1^*}^{Q^*}\left[n_1\int_0^{q_1^*}(D_1)dQ + n_2\int_0^{q_r}(D_2)dQ - \int_0^{Q_r}MC(Q)\ dQ\right]f(Q_s)dQ_s \quad . \ . \ . \ . \ . \ . \ . \ . \ (19)$$

$$\int_{Q^*}^{\infty}\left[n_1\int_0^{q_1^*}(D_1)dQ + n_2\int_0^{q_2^*}(D_2)dQ - \int_0^{Q^*}MC(Q)\ dQ\right]f(Q_s)dQ_s \quad . \ . \ . \ . \ (20)$$

Equation 18 is the expected surplus when $0 \leq Q_s \leq (n_1 + n_2)\ q_1^*$ or the case where the ration allotment is binding for both groups of consumers. Equation 19 pertains when $(n_1 + n_2)\ q_1^* \leq Q_s \leq Q^*$ or the drought is not severe enough for the ration allotment to be binding for consumers in the first group, but it is binding for consumers in the second group. Equation 20 represents the expected surplus when the available water supply exceeds the total quantity of water demanded, Q^*. Therefore, there is no need for rationing.

Two different methods of determining the uniform ration quota q_r are explained below. In one scheme, q_r is determined by dividing available water supply by the total number of consumers. Under this scheme some of the available water may not be used even though rationing is restricting use. In scheme II, q_r is varied as the available water supply falls so that the water supply is always exhausted during rationing.

<u>Rationing Scheme I</u>

In this case, the ration quota is determined by the rule $q_r = Q_s/(n_1 + n_2)$. The available water supply is divided by the total number of households, irrespective of the level of Q_s. When $0 \leq Q_s \leq (n_1 + n_2)q_1^*$, this ration quota will be binding for consumers in both groups, because $0 \leq$

$[Q_s/(n_1 + n_2)] \leq q_1^* \leq q_2^*$. Therefore, all of the available water supply Q_s would be exhausted, and $Q_r = Q_s$. However, when $(n_1 + n_2)\, q_1^* \leq Q_s \leq Q^*$, the ration quota will not be binding for consumers in the first group, because $q_1^* \leq [Q_s/(n_1 + n_2)]$. Therefore, the available water supply Q_s will not be exhausted, and $Q_r = n_1 q_1^* + n_2 q_r < Q_s$.

To extend this model over a number of groups of consumers, suppose that there are m groups of consumers with individual demand functions of the form D_i, $i = 1, 2, 3, \ldots, m$. At Q^* each consuming unit demands $q_i^*(P^*)$, and the ordering of q_i^* are such that

$$q_1^*(P^*) < q_2^*(P^*) < q_3^*(P^*) < \ldots\ldots < q_m^*(P^*)$$

Each group has n_i consumers. Define $n = n_1 + n_2 + \ldots + n_m$ as the total number of households. The ration quota is set equal to $q_r = Q_s/n$ whenever Q_s falls short of Q^*. With these assumptions, the expected surplus, ES, could be defined as the sum of Equations 21 through 24:

$$\int_0^{nq_1^*} \left[n_1 \int_0^{q_r} (D_1)\,dQ + n_2 \int_0^{q_r} (D_2)\,dQ + \ldots\ldots + n_m \int_0^{q_r} (D_m)\,dQ - \int_0^{Q_r} MC(Q)\,dQ \right] f(Q_s)\,dQ_s \quad \ldots (21)$$

$$\int_{nq_1^*}^{nq_2^*} \left[n_1 \int_0^{q_1^*} (D_1)\,dQ + n_2 \int_0^{q_r} (D_2)\,dQ + n_m \int_0^{q_r} (D_m)\,dQ - \int_0^{Q_r} MC(Q)\,dQ \right] f(Q_s)\,dQ_s \quad \ldots (22)$$

$$\vdots$$

$$\int_{nq_j^*}^{Q^*} \left[n_1 \int_0^{q_1^*} (D_1)\,dQ + n_2 \int_0^{q_2^*} (D_2)\,dQ + \ldots + n_j \int_0^{q_j^*} (D_j)\,dQ + n_{j+1} \int_0^{q_r} (D_{j+1})\,dQ + \ldots + n_m \int_0^{q_r} (D_m)\,dQ - \int_0^{Q_r} MC(Q)\,dQ \right] f(Q_s)\,dQ_s \quad \ldots (23)$$

$$\int_{Q^*}^{\infty} \left[n_1 \int_0^{q_1^*} (D_1)\,dQ + n_2 \int_0^{q_2^*} (D_2)\,dQ + \right.$$

$$\ldots\ldots + n_m \int_0^{q_m^*} (D_m)dQ -$$

$$\left.\int_0^{Q^*} MC(Q)dQ \right] f(Q_s)dQ_s \quad \ldots\ldots (24)$$

Equation 21 shows the portion of the expected surplus when $0 < Q_s < nq_1^*$. The ration quota q_r is binding for consumers in all m groups, because $(Q_s/n) \leq q_1^* < q_2^* < \ldots. < q_m^*$ and therefore $Q_r = Q_s$. Equation 22 shows the portion of the expected surplus when $nq_1^* \leq Q_s \leq nq_2^*$. In this case, ration quota is not binding for consumers in the first group, but it is binding for consumers in all other groups, because $q_1^* \leq (Q_s/n) \leq q_2^* < \ldots. < q_m^*$, and therefore $Q_r = n_1q_1^* + (n_2 + \ldots + n_m)q_r$.

Equation 23 shows the portion of expected surplus when $nq_j^* \leq -Q_s \leq Q^*$, and therefore the ration quota is not binding for consumers in groups 1, 2, ..., j; but it is binding for consumers in groups j + 1, ..., m; because:

$$q_1^* < q_2^* < \ldots. < q_j^* \leq (Q_s/n)$$
$$\leq q_{j+1}^* < \ldots < q_m^*$$

and therefore $Q_r = n_1q_1^* + n_2q_2^* + \ldots + n_jq_j^* + (n_{j+1} + \ldots + n_m)q_r$. In order to find j, the demand functions of consumers in all m groups are assumed to be linear and have a common intercept term, with different slopes. The inverse demand functions will be of the form $P_i = \alpha - \beta_i q$. The quantity demanded by the ith group consumer is $q_i^* = k_i Q^*$ where

$$k_i = \frac{1}{\beta_i \left(\frac{n_1}{\beta_1} + \frac{n_2}{\beta_2} + \ldots. + \frac{n_m}{\beta_m}\right)}$$

When $nq_j^* \leq Q_s \leq Q^*$ or

$q_j^* \leq (Q_s/n) \leq (Q^*/n)$, it implies that $(Q^*/n) \geq q_j^*$.

Upon substituting $k_j Q^*$ for q_j^*, the above inequality becomes

$$(Q^*/n) \geq k_jQ^*, \text{ or } (1/n) \geq k_j$$
$$> k_{j-1} > \ldots. > k_1.$$

This suggests that j can be determined by

$$\frac{1}{n} - k_j = \underset{i}{\mathrm{Min}} \left\{\frac{1}{n} - k_i;\ \frac{1}{n} - k_i \geq 0\right\}$$

Equation 24 shows the expected surplus when $Q_s \geq Q^*$. In this case, there is no need for nonprice rationing.

If assumption of equal intercept terms is relaxed, then discrete approximation will be required. The problem can be solved using integer programming techniques.

<u>Rationing Scheme II</u>

In order to exhaust the available water supply under non-price rationing (when Q_s falls short of Q^*), the ration quota has to be varied with Q_s. When $0 \leq Q_s \leq (n_1 + n_2)\, q_1^*$, then $q_r = Q_s/(n_1 + n_2)$ would be binding for consumers in both groups and therefore Q_s would be exhausted. When $(n_1 + n_2)\, q_1^* \leq Q_s \leq Q^* = n_1q_1^* + n_2q_2^*$, then $q_r = (Q_s - n_1q_1^*)/n_2$ would not be binding for consumers in the first group, but would be binding for consumers in the second group. This would lead to the exhaustion of available water supply, because unlike scheme I, determination of q_r is made based on the fact that it would not be binding for consumers of the first group. Therefore, in this scheme Q_r would always be equal to Q_s. The model can be extended to m groups of consumers under the same assumptions as rationing scheme I.

The expected surplus, ES, would be defined by the sum of Equations 25 through 29:

$$\int_0^{\sum_{i=1}^{m} n_i \cdot q_1^*} \Bigg[n_1 \int_0^{q_{r,1}} (D_2)dQ$$

$$+ n_2 \int_0^{q_{r,2}} (D_2)dQ$$

$$+ n_3 \int_0^{q_{r,1}} (D_3)dQ + \ldots. + n_m \int_0^{q_{r,1}} (D_m)dQ -$$

$$\int_0^{Q_s} MC(Q)dQ \Bigg] f(Q_s)dQ_s \quad . \quad . \quad . \quad (25)$$

$$+ \ldots. + n_m \int_0^{q_{r,2}} (D_m)dQ -$$

$$\int_0^{Q_s} MC(Q)dQ \Bigg] f(Q_s)dQ_s \quad . \quad . \quad . \quad (26)$$

$$\int_{n_1 q_1^* + \sum_{i=2}^{m} n_i \cdot q_2^*}^{n_1 q_1^* + n_2 q_2^* + \sum_{i=3}^{m} n_i \cdot q_3^*}$$

$$\Bigg[n_1 \int_0^{q_1^*} (D_1)dQ + n_2 \int_0^{q_2^*} (D_2)dQ +$$

$$\int_{\sum_{i=1}^{m} n_i \cdot q_1^*}^{n_1 q_1^* + \sum_{i=2}^{m} n_i \cdot q_2^*} \Bigg[n_1 \int_0^{q_1^*} (D_1)dQ + n_3 \int_0^{q_{r,3}} (D_3)dQ + \ldots.. +$$

$$n_2 \int_0^{q_{r,2}} (D_2)dQ + n_3 \int_0^{q_{r,2}} (D_3)dQ$$

$$n_m \int_0^{q_{r,3}} (D_m)dQ - \int_0^{Q_s} MC(Q)dQ \Bigg] f(Q_s)dQ_s$$

$$. \quad . \quad . \quad (27)$$

$$\int_{\sum_{i=1}^{m-2} n_i q_i^* + (n_{m-1} + n_m) q_{m-1}^*}^{Q^*}$$

$$\left[n_1 \int_0^{q_1^*} (D_1)dQ + n_2 \int_0^{q_2^*} (D_2)dQ + \ldots + \right.$$

$$n_{m-1} \int_0^{q_{m-1}^*} (D_{m-1})dQ + n_m \int_0^{q_{r,m}} (D_m)dQ$$

$$\left. - \int_0^{Q_s} MC(Q)dQ \right] f(Q_s)dQ_s \quad \ldots \text{(28)}$$

$$\int_{Q^*}^{\infty} \left[n_1 \int_0^{q_1^*} (D_1)dQ + n_2 \int_0^{q_2^*} (D_2)dQ \right.$$

$$+ \ldots + n_m \int_0^{q_m^*} (D_m)dQ \quad -$$

$$\left. \int_0^{Q^*} MC(Q)dQ \right] f(Q_s)dQ_s \quad \ldots \text{(29)}$$

In Equation 25, when

$$0 \leq Q_s \leq \sum_{i=1}^{m} n_i \quad q_1^* = (n_1+n_2+ \ldots + n_m) \; q_1^*;$$

the ration quota is set equal to

$$q_{r,1} = \frac{Q_s}{n_1 + n_2 + \ldots + n_m} \quad ; \text{ and}$$

$$q_{r,1} \leq q_1^* < q_2^* < \ldots < q_m^*$$

and as it is binding for consumers in the first group, it is also binding for consumers in all groups.

In Equation 26, when

$$\sum_{i=1}^{m} n_i \cdot q_1^* \leq Q_s \leq n_1 q_1^* + \sum_{i=2}^{m} n_i \cdot q_2^*$$

i.e., when $(n_1 + n_2 + \ldots + n_m) \; q_1^* \leq Q_s \leq n_1 q_1^* + (n_2 + n_3 + \ldots + n_m) \; q_2^*$, the ration quota is set equal to

$$q_{r,2} = \frac{Q_s - n_1 q_1^*}{(n_2 + n_3 + \ldots \; n_m)} \; .$$

The lower and upper limits of Q_s would imply that $q_1^* < q_{r,2} < q_2^* < q_3^* < \ldots < q_m^*$, so that ration quota is binding for consumers of all, except the first group.

In Equation 27, when

$$n_1 q_1^* + \sum_{i=2}^{m} n_i \cdot q_2^* \leq Q_s \leq n_1 q_1^* + n_2 q_2^* + \sum_{i=3}^{m} n_i \cdot q_3^*$$

i.e., when

$$n_1 q_1^* + (n_2 + n_3 + \ldots + n_m)\, q_2^* \leq Q_s \leq n_1 q_1^* + n_2 q_2^* + (n_3 + \ldots + n_m)\, q_3^*,$$

the ration quota is set equal to

$$q_{r,3} = \frac{Q_s - n_1 q_1^* - n_2 q_2}{n_3 + \ldots + n_m}.$$

and lower and upper limits of Q_s would imply that $q_1^* < q_2^* \leq q_{r,3} \leq q_3^* < \ldots < q_m^*$. The ration quota would be binding for consumers of all, except the first and second groups.

In Equation 28, when

$$\sum_{i=1}^{m-2} n_i q_i^* + (n_{m-1} + n_m)\, q_{m-1}^* < Q_s < \sum_{i=1}^{m} n_i q_i^* = Q^*$$

i.e., when

$$n_1 q_1^* + \ldots + n_{m-2}\, q_{m-2}^* + (n_{m-1} + n_m)\, q_{m-1}^* \leq Q_s \leq n_1 q_1^* + \ldots + n_m\, q_m^*;$$

the ration quota is set equal to

$$q_{r,m} = \frac{Q_s - n_1 q_1^* - \ldots - n_{m-1}\, q_{m-1}^*}{n_m}.$$

The lower and upper limits of Q_s imply that $q_1^* < q_2^* < \ldots < q_{m-1}^* \leq q_{r,m} \leq q_m^*$, so that the ration quota is binding only for consumers of the last (mth group).

Equation 29 shows the expected surplus when the available water supply exceeds the total quantity of water demanded at optimal price P^*. In this situation, there is no need for resorting to nonprice rationing schemes.

Benefit Maximization

The benefit functions for the two rationing schemes presented above are highly nonlinear. Maximization of these functions without any constraints would suggest different prices for different consumer groups. If the effect of different rates on intramarginal units on demand is negligible (Taylor 1975, Billings and Agthe 1980), these different prices define a multiple block rate structure.

However, by introducing some constraints to the problem, uniform pricing schedules could alternatively be determined. The necessary constraints are derived from the individual inverse demand functions of different groups. Suppose that the inverse demand functions are linear in the regions of concern and are of the forms:

$$D_1: \quad P_1 = \alpha_1 - \beta_1 q$$

$$D_2: \quad P_2 = \alpha_2 - \beta_2 q$$

$$D_3: \quad P_3 = \alpha_3 - \beta_3 q$$

$$D_4: \quad P_4 = \alpha_4 - \beta_4 q$$

$$\vdots \qquad \vdots$$

$$D_m: \quad P_m = \alpha_m - \beta_m q$$

In order to have a uniform pricing schedule, the prices will have to be made equal in the inverse demand functions, i.e.:

$$P_1 = P_2 \; ; \; P_2 = P_3 ; \; P_3 = P_4 , \; \ldots ,$$

$$P_{m-1} = P_m$$

which would yield the following constraints:

$$(\alpha_1 - \alpha_2) - \beta_1 q_1 + \beta_2 q_2 = 0$$

$$(\alpha_2 - \alpha_3) - \beta_2 q_2 + \beta_3 q_3 = 0$$

$$(\alpha_3 - \alpha_4) - \beta_3 q_3 + \beta_4 q_4 = 0$$

$$\vdots$$

$$(\alpha_{m-1} - \alpha_m) - \beta_{m-1} q_{m-1} + \beta_m q_m = 0$$

The optimal value of the ES corresponding to the constrained problems would be lower than the solutions to unconstrained problems.

As a whole, these models define water shortages as a function of price and available water supply. The short run price rigidity, which is one of the characteristics of the water market, is incorporated. Under the condition of fixed prices in short run, two methods of quantity rationing are proposed to deal with water shortages. Finally, economically efficient long run prices which are consistent with these rationing rules are derived.

Description of the Case Study Area

The model developed in the previous section was applied to the major water retailer in Salt Lake County, namely the Water Department in the Salt Lake City Department of Public Utilities. Salt Lake County is surrounded on three sides by mountains and Great Salt Lake on the north. The Wasatch Range forms the eastern boundary; the Traverse Mountains the southern and the Oquirrh Mountains the western boundary. The Jordan River, which has poor quality water used mainly for industrial and agricultural purposes, enters the county below the outlet of Utah Lake and flows north through Salt Lake County, dividing it into eastern and western portions, and terminates in the Great Salt Lake (Figure 8). The streams originating in the Wasatch Range, which are sources of high quality water, provide more than 97 percent of the surface water supply originating in the Salt Lake Valley drainage area. The seven major streams from north to south are City, Red Butte, Emigration, Parleys, Mill, Big Cottonwood, and Little Cottonwood Creeks. The streams originating in the Oquirrh Mountains provide less than 3 percent of the surface water supply originating in the Salt Lake Valley drainage area.

Presently, the major source of imported water into Salt Lake County is from the Deer Creek Reservoir on the Provo River. The Central Utah Project does not as yet supply any water to Salt Lake County. The Bonneville Unit, which is part of the Central Utah Project's initial phase, will divert Uintah Basin water (in eastern Utah) to Bonneville Basin (north-central Utah). Of the 100,000 acre-feet of municipal and industrial water that will be developed, 70,000 acre-feet will be available for Salt Lake County.

There were nearly 12,000 wells in the valley registered with the Utah Division of Water Rights in 1969. The majority of the wells are located to the east of Jordan River where the quality of the water is generally high.

Over 42 percent of Utah's population resides in Salt Lake County, which is the primary industrial, political, and commercial center of the Inter-

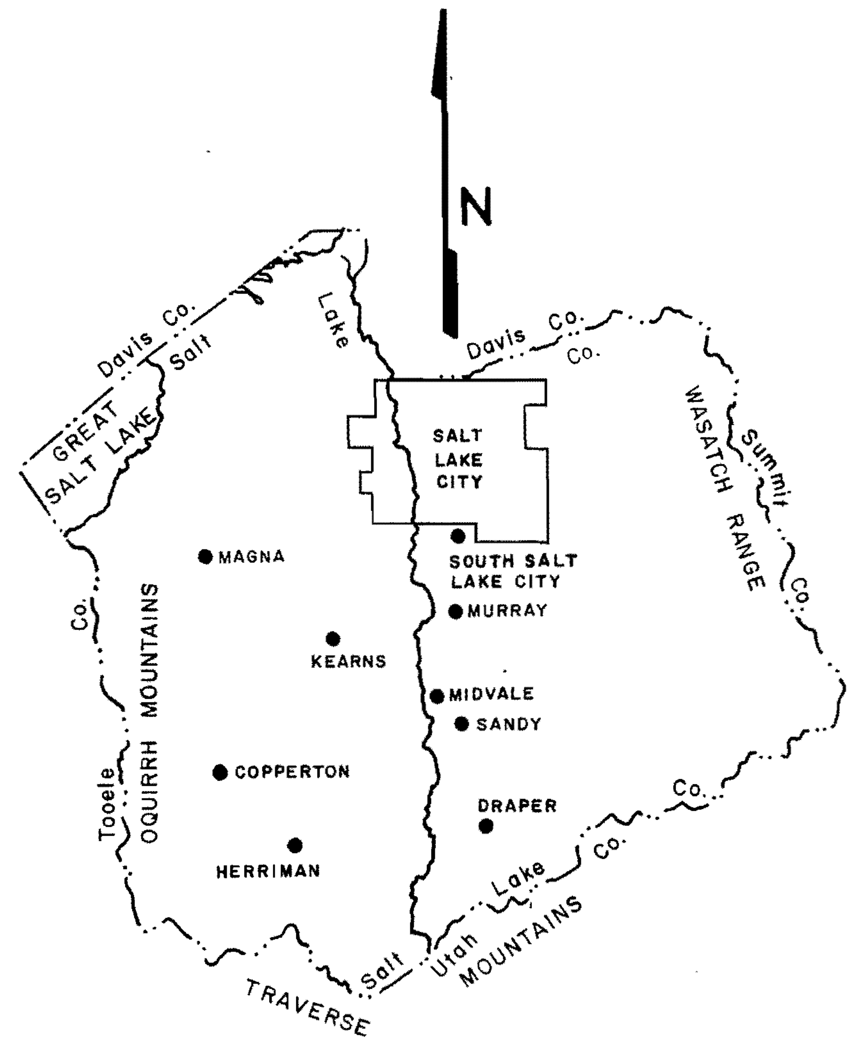

Figure 8. Salt Lake County.

mountain West. During the period of 1960 to 1980, the population in Salt Lake County increased 62 percent, to 620,000, and it is expected to rise to nearly 1 million by the turn of the century.

Of the 657,700 acre-feet of water withdrawn during 1980 in Salt Lake County, 167,700 acre-feet (25.5 percent) were used for municipal purposes, 161,500 acre-feet (24.5 percent) for industrial, 294,900 acre-feet (45 percent) for irrigation, and 33,600 acre-feet (5 percent) for rural domestic and livestock.

The current annual municipal water supply in Salt Lake County under average precipitation conditions is estimated to be 185,000 acre-feet. If this supply was to remain the same, it is projected that water consumption would exceed available supply by 1985 (presumably at current prices); and by the year 2000, it would exceed supply by nearly 70,000 acre-feet. About 40 to 50 percent of the annual municipal water delivered is used outdoors for lawns and gardens (Metropolitan Water District of Salt Lake City et al. 1982).

The Water Department in the Salt Lake City Department of Public Utilities

(Salt Lake City Water Department) is by far the biggest municipal water retailer in Salt Lake County. It delivered more than 92,000 acre-feet of water to a population of nearly 370,000 people during 1979-80 water year (including daytime work force and tourists). On the average, 16.1 percent of its supplies comes from pumps and artesian wells, 1.2 percent from springs, and the rest (83 percent) from surface sources of water. Because of this large dependency on the stochastically variable surface supply, the Salt Lake City Water Department was found ideal for this study. Salt Lake City Water Department has water rights to City, Emigration, Parleys, Mill, Big Cottonwood, and Little Cottonwood Creeks. The details for these water rights were obtained from Salt Lake City Water Department. The water right structure is quite complicated in terms of the time, quantity, and the priority components of the water rights. For modeling purposes, they were simplified, based on past use levels from these streams as shown in Table 3.

Since Salt Lake City Water Department has primary rights to most of these creeks (for those that it doesn't have the primary rights, the share of primary right holders to streamflow was not significant), this simplification seemed to be appropriate and was judged to show the actual obtainable water from these creeks.

Seasonal Analysis

The Salt Lake City Water Department maintains an excellent data record on monthly water consumption and sources of water supply. Average monthly water consumptions for the period 1971-1981 were calculated. The year 1977 was excluded from this calculation because of rationing measures that were implemented for drought mitigation. These averages are plotted in Figure 9. Based on these averages and the seasonal analysis performed by Hansen and Narayanan (1981), the months of the year were divided into growing and nongrowing seasons. May through September was judged to be the growing season, whereas October through April was recognized as the nongrowing season. As mentioned earlier, about 40 to 50 percent of the annual municipal water consumption is for outdoor uses. Since this outdoor use occurs in the growing season, water management is more critical for the growing season months than for the nongrowing season months. In other words, any water shortage would most probably occur in the growing season, when the demand for water is relatively high.

Based on the data from 1970-1981, the amount of water withdrawn from each source and its percentage contribution to the total water delivered was calculated for the growing season. These percentages for year 1977 (the drought

Table 3. Water rights of Salt Lake City Water Department.

Creek	City	Emigration	Parleys	Mill	Big Cottonwood	Little Cottonwood
Water right to percentage of flow	100%	50%	100%	50%	75%	50%

year) and their averages for the whole period are shown in Table 4.

It is interesting to note that these percentages were not drastically different during the drought of 1977 as compared to normal water conditions. The major differences were a decline in Parley Creek's contribution and corresponding increases in the Little Cottonwood and Deer Creek contributions.

Demand Estimation

In order to apply the above theoretical model, demand functions are needed for several groups of water users. Assuming that there are m groups

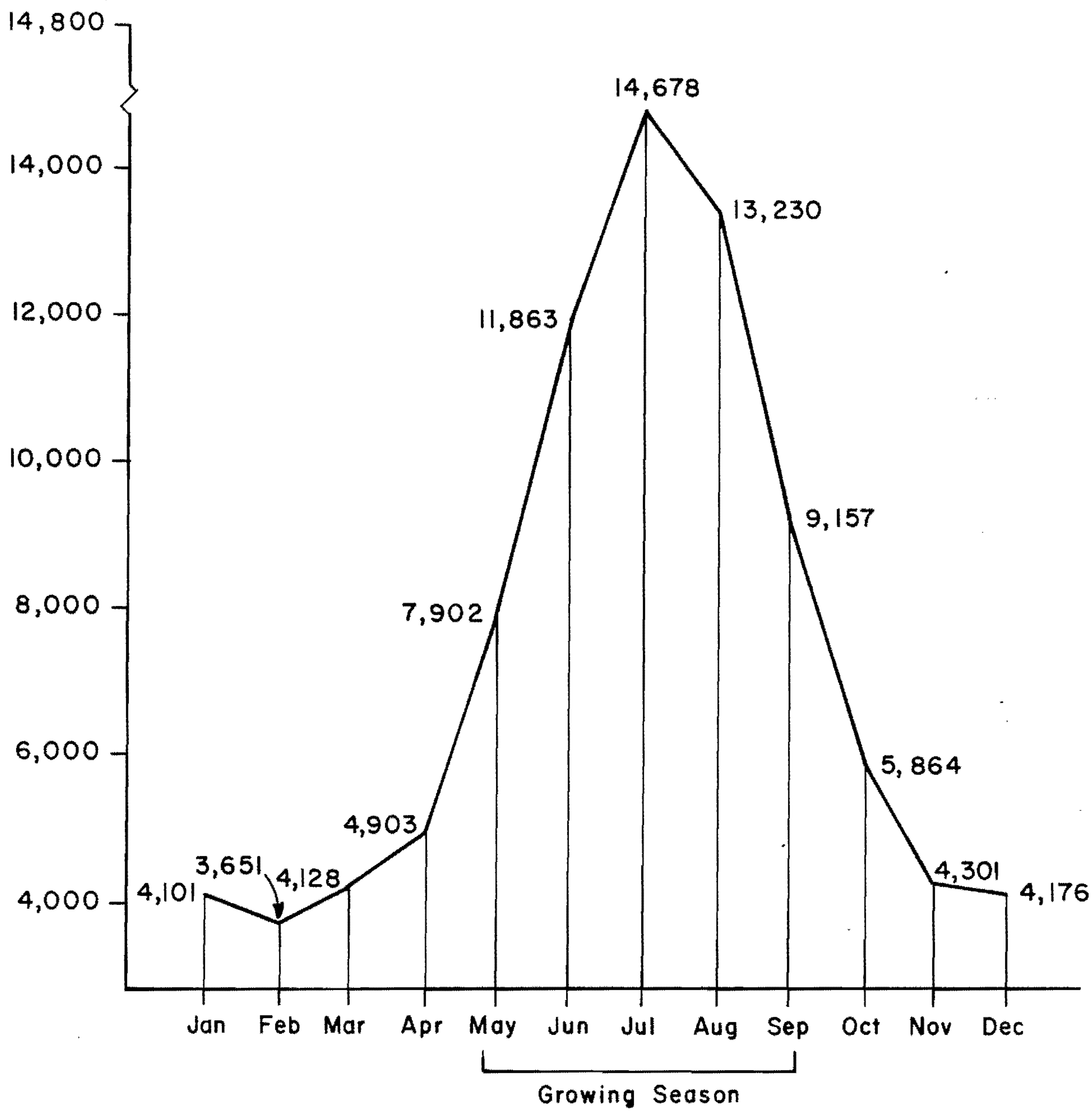

Figure 9. Average monthly water consumption (acre-feet).

Table 4. Contribution of each source of supply of total water delivered.

Source	City Creek	Emigration Creek	Parley's Creek	Big Cottonwood Creek	Little Cottonwood Creek	Deer Creek Reservoir	Pump Wells	Artesian Wells	Springs
Year 1977	8%	1.6%	7%	23%	20%	22%	12%	5%	1.4%
Average of 1970-81	8.5%	1.8%	13.2%	24.2%	17.5%	17.4%	12.8%	3.3%	1.3%

of consumers and that consumers in any group have similar demand functions, m demand functions are needed. There are no available studies on the distribution of water demand among consumers within a community. However, numerous studies estimate the aggregate water demand for communities in the United States. For example, Hansen and Narayanan (1981) estimated the elasticity of demand for water in Salt Lake City, Utah, from Salt Lake City Water Department data. If the demand functions of different groups of water users are linear with common intercepts, the slopes and intercept terms of the demand could be estimated using the data for elasticity, existing prices, and quantities of water consumed by the individual households belonging to different groups.

Hansen and Narayanan (1981) formulated a multivariate time series model to study monthly variations in water demand. The left-hand side variable in their multivariate regression model was municipal water demand and the right-hand side contained price, average temperature, total precipitation, and percentage of daylight hours. They applied this model to Salt Lake City Water Department data and obtained an expression with a high multiple correlation coefficient and F-statistics. Also, in ex post forecast, their model accurately predicted monthly variation in municipal water demand. They reported a price elasticity of -0.469, and this vlaue is used in estimating the demand functions needed in this study.

Two other sets of data needed for estimation of the demand functions are the price of water and the distribution of quantities of water consumed by households at these prices. These data were collected from records of the Salt Lake City Water Department for the growing season of 1981. Salt Lake City Water Department has two price structures, one for customers within the city limit and one for customers outside the city limit (county customers).

The price structure for the period under question is shown in Table 5. The marginal prices of $0.25 and $0.37 per 100 cubic feet were used since nearly all the customers used more than 1000 cu. ft.

As this study is mainly concerned with residential water demand, a random sample of size 125 was drawn from meter readings of water connections up to 1 inch served by the Salt Lake City Water Department. Sixty-nine of these customers were in the city limits, and the remaining 56 meter readings were in the county. The bimonthly meter readings were adjusted for and summed to show the water consumption during the period of May-September 1981. A price of $0.25 per 100 cubic feet was used as the base for calculating the demand function, the quantities consumed by customers paying the higher county rate were adjusted upward by using the price elasticity of -0.469 to estimate their consumption at the price of $0.25 per 100 cubic feet. The next step was to group the consumers according to the amount of water they consumed during May-September 1981 as shown in Table 6.

Table 5. Salt Lake City Water Department 1981 price structure.

City	$3.50/1st 1000 Cubic Feet	$0.25/100 Cubic Feet Extra
County	$5.00/1st 1000 Cubic Feet	$0.37/100 Cubic Feet Extra

Table 6. Residential consumer groupings by May-September water consumption.

Group Range in 100 ft^3	Frequency	Percent of Total	Sample Mean u	Second Sample Moment u_2'	$\frac{\sqrt{u2'}}{u}$
0-200	56	45	128.27	18,814.6	1.07
200-400	31	25	276.45	80,664.5	1.03
400-600	30	25	492.67	245,967.4	1.007
600-900	7	5	735.0	544,857.9	1.004

Several grouping ranges were tried before one was chosen. The grouping chosen has equal consumption ranges and the standard deviation of each group is approxmately the same. This can be seen by the increasing ratios of the square root of u_2' to u among the groups. This ratio is similar to the coefficient of variation, with the difference being that the standard deviation (square root of second central moment) is replaced by the square root of second ordinary moment u_2'. As shown in Table 6, 45 percent of the population is in a group consuming an average of 128.27 (100 ft^3), 25 percent consuming 276.45 (100 ft^3), 25 percent consuming 492.67 (100 ft^3) and 5 percent consuming 735.0 (100 ft^3), from May through September at a given price of \$0.25/100 ft^3.

Data were also collected from the Salt Lake City Water Department on the number of water connections for year 1981. Table 7 shows numbers of connections by pipe size for both the city and county. There were 72,124 connections up to 1 inch. These are assumed to be the residential or household customers. Dividing proportional to the percentages in the random sample reported in Table 6, the numbers of consumers in the four groups are n_1 = 32,456, n_2 = 18,031, n_3 = 18,031, and n_4 = 3,606.

The data for streamflows, used to estimate the water supply probability density function, were on an acre-foot basis, and all of the demand data were converted to acre-feet. A price of \$0.25/100 cubic feet is equivalent to \$108.90 per acre-foot, and the mean water consumptions for the four groups are:

Group	Sample Mean of of Water Consumption (Acre-foot)
1	0.2945
2	0.6346
3	1.1310
4	1.6873

These amounts of water consumption at a price of \$108.90, with a price elasticity of -0.469, imply the following demand functions, which have a common intercept term:

Group 1 (D1): $P_1 = 341.0962 - 788.44\ q$

Group 2 (D2): $P_2 = 341.0962 - 365.89\ q$

Group 3 (D3): $P_3 = 341.0962 - 205.30\ q$

Group 4 (D4): $P_3 = 341.0962 - 137.61\ q$

Table 7. Number of water connections by size (1981).

Water Connection Size	City	County	Total
Up to 1 inch	46,969	25,155	72,124
1" to 2"	1,556	337	1,893
2" to 10"	569	82	651
Total	49,094	25,574	74,668

Based on these demand functions, the estimated water consumption during the growing season of 1981, at the given price would be

$$\sum_{i=1}^{4} n_i q_i = 47{,}478.3 \text{ acre-feet}$$

The actual water consumption during the period was 58,892.7 acre-feet. The difference of 11,414.4 acre-feet is attributed to water consumption through the connections larger than 1 inch that were excluded from the sample in this study. However, this is taken care of in estimation of available water supply by shifting the probability density function.

Supply Estimation

Since the appropriate data for estimating the marginal cost function were not available, the marginal cost was assumed to equal the average cost. The average cost was estimated by dividing the total operating expenses by total water consumption (production):

$$AC\ (1980) = \frac{\text{Total Operating Expenses}}{\text{Total Water Consumption}} = \frac{9{,}792{,}907}{92{,}207}$$

$$= \$106.20/\text{acre-foot}$$

These data were obtained from the annual report of Salt Lake City Water Department (1979-1980).

The model in Chapter II requires description of the variable water supply with a probability density function. Assume that the available water supply, Q_s, has a transformed beta distribution with the following density function:

$$f(Q_s) = \begin{cases} \dfrac{\Gamma(\gamma+\delta)}{A^{(\gamma+\delta-1)} \cdot \Gamma(\gamma) \cdot \Gamma(\delta)} (Q_s - B)^{\gamma-1} (A+B-Q_s)^{\delta-1} & \text{for } B < Q_s < A + B \\ 0 & \text{elsewhere} \end{cases}$$

This density function limits the minimum and maximum water supply to B and A+B, respectively. It has a flexible functional form and is quite well suited to model stochastic flows. Figure 10 shows histograms for historical data as well as estimated density function.

This density function has four parameters which can be estimated by the method of moments. The first four ordinary moments of this function are given by:

$$u_1' = B + A \frac{\gamma}{\gamma + \delta}$$

$$u_2' = A^2 \frac{(\gamma + 1)\gamma}{(\gamma + \delta + 1)(\gamma + \delta)} + 2BA \frac{\gamma}{\gamma + \delta} + B^2$$

$$u_3' = A^3 \frac{(\gamma + 2)(\gamma + 1)\gamma}{(\gamma + \delta + 2)(\gamma + \delta + 1)(\gamma + \delta)} + 3BA^2 \frac{(\gamma + 1)\gamma}{(\gamma + \delta + 1)(\gamma + \delta)} + 3B^2A \frac{\gamma}{(\gamma + \delta)} + B^3$$

$$u_4' = A^4 \frac{(\gamma+3)(\gamma+2)(\gamma+1)\gamma}{(\gamma+\delta+3)(\gamma+\delta+2)(\gamma+\delta+1)(\gamma+\delta)} + 4BA^3 \frac{(\gamma+2)(\gamma+1)\gamma}{(\gamma+\delta+2)(\gamma+\delta+1)(\gamma+\delta)} + 6B^2A^2 \frac{(\gamma+1)\gamma}{(\gamma+\delta+1)(\gamma+\delta)} + 4B^3A \frac{\gamma}{(\gamma+\delta)} + B^4$$

These four parameters (γ, δ, B and A can be estimated from the four sample moments; however, the solutions may not be unique. In order to calculate the sample moments, measurements of the water supply available to the Salt Lake City Water Department during the May through September growing seasons was obtained for a number of years for which data were available.

In a "Salt Lake County Area-wide Water Study," prepared by a group of engineers for the three major water utilities of Salt Lake County (Metropolitan Water District of Salt Lake City et al. 1982), streamflows for the six Wasatch creeks are listed on a monthly basis. The Salt Lake City Water Department depends largely on these sources. The water rights of the Salt Lake City Water Department presented in Table 3 as percentages of total streamflow were multiplied by the respective water flows and the products were summed over the six creeks and then over the May-September months for the period of 1911-1980.

The first four ordinary moments were calculated from the 70 observations. In order to estimate the four parameters of the density function, the sample moments could be equated to the population moments in the four equations given above. One could solve for the four unknown parameters, but the solution would be difficult. Therefore, it was assumed that the lower limit of density function, B is equal to zero, and the remaining three parameters were estimated using the first three sample moments and the corresponding equations. However, the results were not satisfactory because the resulting density function did not cover about 20 percent of the observations in the sample. A second simplification was made by setting the upper limit, A+B, to the sample maximum.

The data for estimation of parameters and the estimated values of γ and δ are shown below:

First sample moment $m_1' = 69{,}062.5$

Second sample moment $m_2' = 5{,}267{,}714{,}560$

$B = 0$

$A+B = A =$ sample maximum $= 127{,}210$

and the parameter estimates: $\begin{cases} \hat{\gamma} = 3.8340 \\ \hat{\delta} = 3.2281 \end{cases}$

Presently, Salt Lake City Water Department does not use any water from Mill Creek for culinary purposes, even through it has rights to about 50 percent of the flow. But, it is expected that with increased demand, and specially during times of water shortage, the Salt Lake City Water Department will use its entitlement on Mill Creek. Therefore, Mill Creek water was included in the available water supply.

The nonstochastic portion of the available water supply was then calculated and used as a shift parameter for the probability density function. The sources other than the six creeks, net of the water consumption unaccounted for in demand estimation, were assumed nonstochastic. The total water from all sources of supply other than the six creeks are:

Maximum water from all pump wells + average water from Deer Creek Reservoir + average water from artesian wells + average water from Mt. Olympus Spring + average water from Boundary Spring + average water from Lower Boundary Spring

= 9,819.8 + 9,476.6 + 1,804.7

+ 223.8 + 348.8 + 114.0

= 21,787.7 acre-feet

These data were collected from Salt Lake City Water Department usage records and estimated for the period of 1970-1981. Since the water pumped from wells is not stochastic and determined by the authorities in charge, the maximum pumpage during the period was used. However, averages were used for the other sources.

The water consumption not included in the demand function is the actual water consumption during the May-September months of 1981 minus the water consumption estimated from the demand function or 11,414.4 acre-feet.

Therefore, the nonstochastic portion of the water supply available to residential customers would be 21,787.7 - 11,414.4 or 10,373.3 acre-feet. This number was used in shifting the probability density function to the right. The shift adds equally to the lower and upper limits of the density function, namely B and A+B, but does not change the values of the other two parameters, γ and δ. This procedure assumes that those customers not included in the demand estimation, would not be subjected to any rationing at times of water shortage. Figure 10 superimposes the resulting histogram of water supply available to the Salt Lake City Water Department during May-September on the probability density function fitting a beta distribution with the estimated parameters. The fit appears reasonable.

Application of the Model and Results

The model for rationing scheme II, developed in Chapter II, was chosen for application to the case study area. The rationale was that rationing scheme II is more efficient than rationing scheme I in that it always exhausts the available water supply.

In order to solve the equations, a nonlinear optimization program (MINOS) was utilized. The numerical integration for specification of the objective function was accomplished through the Gauss Quadrature method. Depending on whether the problem was constrained or unconstrained, and on the nature of the constraints, the computer runs took 11 to 17 seconds of CPU time.

Block Rate Pricing Results

The solution gives block rate pricing when there are no constraints imposed on the variables q_i's. The only constraints on q_i's were derived from the limits of integration, to make the lower limit of integration less than the upper limit. These amounted to the following three constraints:

$$q_1 \leq q_2$$

$$q_2 \leq q_3$$

$$q_3 \leq q_4$$

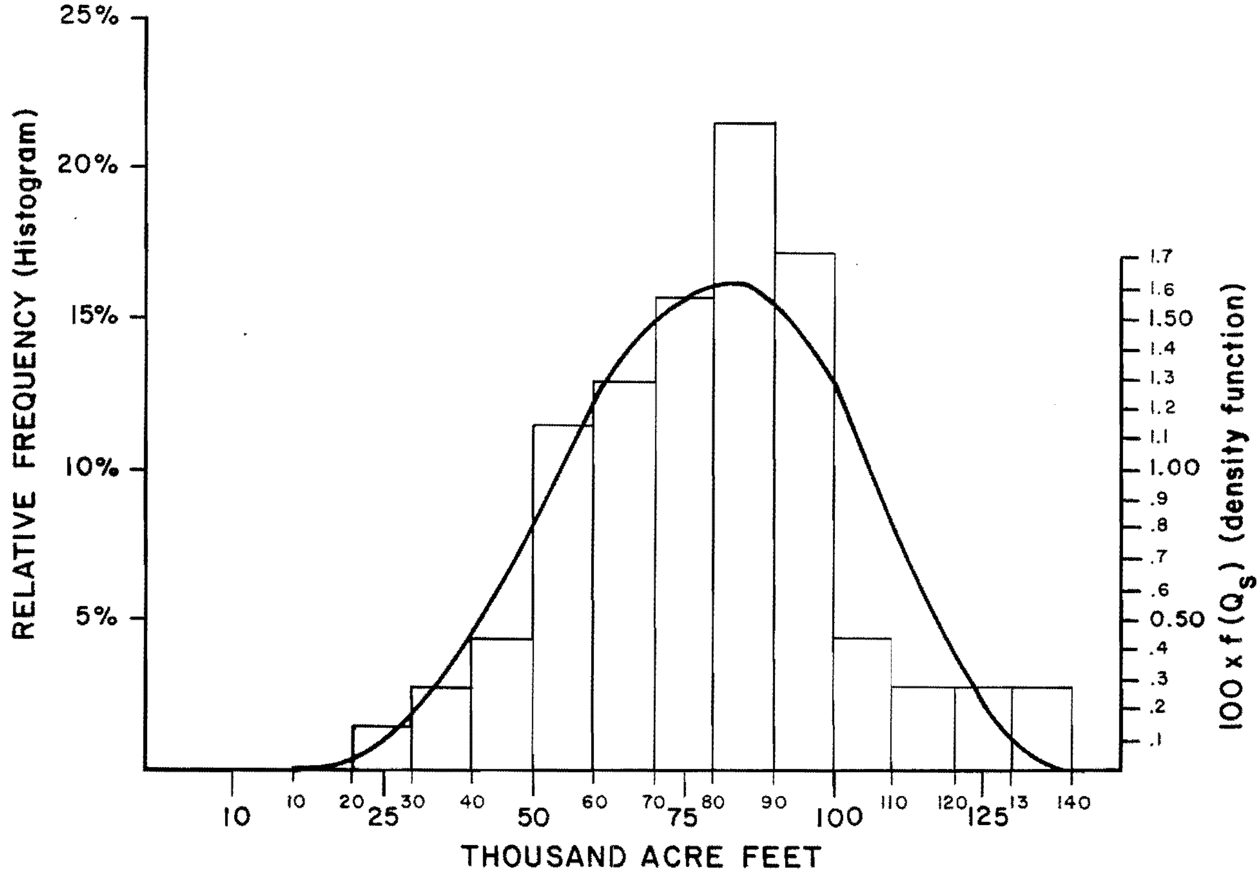

Figure 10. Histogram of probability density function for available water supply in May-September months (1911-1980).

Table 8 shows the results calculated from the demand functions. The results are shown for average cost of $106.20 as well as for increases of 10 and 20 percent. The decreasing price for groups using more water suggests decreasing block rate schedule.

Should average cost increase by 10 percent, the model suggests that the price be raised by 8.5 percent for the first group, 9 percent for the second, 9.8 percent for the third and 10 percent for consumers of the fourth group. If average cost rises by 20 percent, prices should be raised by 17.2 percent for the first group, 18.1 percent for the second, 19.7 percent for the third, and 20 percent for consumers of the fourth group.

Another analysis examined the effects of shifts in the density function of the available water supply, while keeping the average cost at $106.20. If the density functions were shifted to the left (assuming no firm water supply), the lower limit would be zero, and the upper limit would be 127,210 acre-feet. On the other hand if Salt Lake City Water Department was to acquire some 10,000 acre-feet of nonstochastic water supply, perhaps by developing more wells, the probability density function would shift to the right by this amount. The results of

Table 8. Block rate pricing results for three different levels of average cost.[a,b]

	AC = $106.20		AC = $116.82 (10% increase in AC)		AC = $127.44 (20% increase in AC)	
	q	P	q	P	q	P
Group 1	0.291	$111.66	0.279	$120.99	0.267	$130.65
Group 2	0.632	$109.85	0.605	$119.58	0.578	$129.59
Group 3	1.141	$106.85	1.090	$117.24	1.039	$127.77
Group 4	1.707	$106.20	1.630	$116.82	1.553	$127.44
Total demand	47,594		45,515		43,420	
Value of objective function	$5,604,754		$5,117,119		$4,649,832	

[a]Quantities demanded q_i are all in acre-feet.
[b]Costs and prices are all per acre-foot.

these two cases are presented in Table 9.

The results show that a shift of the density function to the left would increase the optimal prices and that a shift to the right would decrease the optimal prices charged to all the consumers except those in Group IV. Table 10 shows rationing rules by water supply ranges and the probabilities associated with them. It also shows the group(s) for which the ration quota is binding. These rationing rules and ranges of water supply are derived for AC = $106.20. According to the top row in the table, rationing for the ordinary residential water user would only be necessary for the 1000-year (0.10 percent probability) drought.

Uniform Rate Pricing Results

In order to derive an optimal uniform price for consumers of all groups, the objective function was constrained and then solved. The following three constraints were derived from the four individual household demand functions and used for problem solution.

$$\text{Constraint 1:} \quad 2.15486\, q_1 - q_2 = 0.0$$

$$\text{Constraint 2:} \quad 1.78222\, q_2 - q_3 = 0.0$$

$$\text{Constraint 3:} \quad 1.49190\, q_3 - q_4 = 0.0$$

Solutions of the constrained problem, along with the uniform optimal prices, are shown in Table 11 for original average cost of $106.20, as well as for the increases in average cost of 10 and 20 percent. These results suggest that if average cost increases by 10 percent, the price charged to consumers should be raised by 9.3 percent, and if average cost increases by 20 percent, price should be raised by 18.8 percent.

Table 9. Block rate pricing results: shifts in probability density function of water supply.[a]

	(Shift to Left) $0.0 \leq Q_s \leq 127,210$		(Shift to Right) $20,373.3 \leq Q_s \leq 147,583.3$	
	q	P	q	P
Group 1	0.283	$118.12	0.296	$107.84
Group 2	0.623	$112.91	0.638	$107.56
Group 3	1.140	$107.11	1.143	$106.46
Group 4	1.707	$106.20	1.707	$106.20
Total demand	47,130		47,873	
Value of objective function	$5,512,020		$5,637,588	

[a]Quantities are all in acre-feet and prices and average costs are all per acre-foot.

Table 12 depicts the situations for uniform pricing when the probability density function of available water supply shifts to the left and right by the same amounts used for the block rate pricing case. The average cost was kept at the original level of $106.20.

Table 13 shows the rationing rules according to the ranges of available water supply, the groups for which rationing is binding, and the probabilities associated with these ranges.

It can be concluded from Tables 10 and 13 that the probability of the water supply falling short of the total demand is about 8.6 percent. On an average, a water shortage is likely to occur about every 12 years for the suggested pricing scheme.

Conclusions and Suggestions for Further Research

If the markets for residential water were not characterized by price rigidity, an instantaneous price adjustment process would have always equated the total quantity demanded with available water supply. In order to account for the stochastic nature of surface water supply, the expected surplus was defined as:

$$ES = \int_B^{Q^*} \left[\int_0^{Q_s} P(Q)dQ - \int_0^{Q_s} MC(Q) \right] f(Q_s)dQ_s$$

Table 10. Rationing rules for the block rate pricing problem according to the range of available water supply.[a]

Range of Water Supply (acre-feet)	Probability (Percent)	Rationing Rule
$10,373.3 < Q_s < 21,001.8$	0.10	$qr = \frac{Q_s}{72,124}$ (Binding for consumers of all 4 groups)
$21,001.8 \leq Q_s \leq 34,538.9$	1.96	$qr = \frac{Q_s - 9,450.9}{39,668}$ (Binding for consumers of groups 2, 3, and 4)
$34,538.9 \leq Q_s \leq 45,554.5$	5.19	$qr = \frac{Q_s - 20,854.6}{21,637}$ (Binding for consumers of groups 3 and 4)
$45,554.5 \leq Q_s \leq 47,593.7$	1.43	$qr = \frac{Q_s - 41,438}{3,606}$ (Binding for consumers of the last group)
$47,593.7 \leq Q_s \leq 137,583.3$	91.4	No rationing needed

[a]Quantities are all in acre-feet.

$$+\int_{Q^*}^{A+B}$$

$$\left[\int_0^{Q^*} P(Q)dQ - \int_0^{Q^*} MC(Q)\right] f(Q_s)dQ_s$$

where P(Q) is the inverse market demand function

$$P = 341.0962 - 0.00489\ Q$$

and the other arguments are the same as defined before. Solving this problem gives

$$Q = 48,035 \text{ acre-feet}$$

$$ES = \$5,620,370$$

which suggests the optimal price to be P = $106.20/acre-feet or the same as the average cost. Therefore in absence of price rigidity, the solutions for the stochastic and deterministic problems are the same.

The difference between the value of the objective function with flexible

Table 11. Uniform rate pricing results for three different levels of average cost.[a,b]

	AC = \$106.20	AC = \$116.82 (10% increase in AC)	AC = \$127.44 (20% increase in AC)
Uniform Price: P	\$108.43	\$118.56	\$128.79
q_1	0.295	0.282	0.269
q_2	0.636	0.608	0.580
q_3	1.133	1.084	1.034
q_4	1.691	1.617	1.543
Total demand	47,574	45,502	43,412
Value of objective function	5,604,339	5,116,862	4,649,677

[a]All quantities are in acre-feet.
[b]Costs and prices are all per acre-foot.

Table 12. Uniform rate pricing results: shifts in probability density function of water supply.[a,b]

	(Shift to left) $0.0 \leq Q_s \leq 127{,}210$	(Shift to Right) $20{,}373.3 \leq Q_s \leq 147{,}583.3$
Uniform Price: P	\$110.99	\$106.98
q_1	0.292	0.297
q_2	0.629	0.640
q_3	1.120	1.140
q_4	1.672	1.701
Total demand	47,052	47,870
Value of objective function	5,510,080	5,637,545

[a]All quantities are in acre-feet.
[b]Costs and prices are all per acre-foot.

Table 13. Rationing rules for the uniform rate pricing problem according to the ranges of available water supply.[a]

Range of Water Supply (acre-feet)	Probability (Percent)	Rationing Rule
$10,373.3 < Q_s < 21,276.6$	0.12	$qr = \frac{Q_s}{72,124}$ (Binding for consumers of all 4 groups)
$21,276.6 \leq Q_s \leq 34,803.4$	2.03	$qr = \frac{Q_s - 9,574.5}{39,668}$ (Binding for consumers of groups 2, 3, and 4)
$34,803.4 \leq Q_s \leq 45,557.0$	5.12	$qr = \frac{Q_s - 21,042.2}{21,637}$ (Binding for consumers of groups 3 and 4)
$45,557.0 \leq Q_s \leq 47,574.0$	1.41	$qr = \frac{Q_s - 41,471.4}{3,606}$ (Binding for consumers of the last (4th) group)
$47,574.0 \leq Q_s \leq 137,583.3$	91.4	No rationing needed

[a]Quantities are all in acre-feet.

pricing ($5,620,370) and the value of objective function for rigid uniform pricing ($5,604,339) is $16,030. This amount can be regarded as the welfare cost of price rigidity and associated quantity rationing.

Block rate pricing is becoming a common rate structure for public utilities. When "such block system is used marginal values in use will not in general be equated between individuals; some will tend to consume an amount such that they end up in the higher-priced block and others will end up in the lower" (Hirshliefer et al. 1960, p. 45). One interesting result of this study is the suggestion of decreasing block rates for water. A price schedule with decreasing block rates implies that the consumer is, in effect, facing a downward sloping supply schedule (Taylor 1975). Converting the results of Table 8 to a 100 cubic foot basis, which is the unit used by Salt Lake City Water Department, the model suggests the following price schedule for monthly water sales during the growing season:

Price/100 cubic feet	Monthly Water Consumption
\$0.256	up to 25 (100 ft^3)
\$0.250	up to 55 (100 ft^3)
\$0.245	up to 96 (100 ft^3)
\$0.243	up to 149 (100 ft^3)

However, considering the administrative costs of calculating consumer bills with different rates and the small difference between the values of the objective functions for block rate pricing and uniform pricing in Tables 8 and 11, block rate pricing is not justified.

The uniform pricing result of \$108.43 per acre-foot is equivalent to \$0.249 per 100 cubic feet, which is very close to the price of \$0.25 per 100 cubic feet charged to consumers at the time by Salt Lake City Water Department. Therefore, this study concludes that the existing pricing policies of Salt Lake City Water Department are optimal, even when we bring the price rigidity and stochastic water supply into the scenario of price determination.

The models outlined in this study propose second best type solutions to allocating water at times of shortage under price rigidity. The rationing rules derived conform to the actual policies pursued by many water supply utilities during shortages.

Most drought indices provide some physical measurement of drought that is exogenous to the socio-economic system. In contrast, the models presented in this study define drought as an endogenous variable. After selecting the optimal long run prices, drought is defined as the cases where water supply Q_s falls short of Q^*, the total quantity of water demanded at these optimal prices. This definition is more suitable for policy purposes and follows the principle suggested by Howe et al. (1980, p. 4) of entering the expectation of water users into the definition of drought.

Another characteristic of the models is that the price charged to consumers would be greater than marginal cost in order to minimize the welfare loss resulting from rationing. The greater the welfare loss of rationing, the more the deviation from marginal cost. Rationing scheme I has greater welfare losses (due to cases of non-exhaustion of water supply at times of rationing) than does rationing scheme II. Had rationing scheme I been applied in this study, it would have given higher prices.

One direction for further research would be to examine the effect of reservoirs for water storage. In this case, calculation of Q_s, the available water supply for each period, would add the amount of water in the reservoir at the beginning of the period to the amount of runoff during the period. Another study could examine multiple sources of supply. If consumers of different localities were to be served from different sources, separate probability density functions would be needed.

On the demand side, more effort could be placed on estimation of multiple group demand functions and on rationing rules based on a percentage of previous use. If the agricultural, industrial, and municipal demand functions for water could be estimated separately, the model could be used for optimal intersectoral allocation of water.

CHAPTER IV

ESTIMATED INEFFICIENCIES OF SHORT-TERM WATER RESOURCES IMMOBILITY DURING DROUGHT

Introduction

Short-term Resources Immobility

The net economic benefits of resource use equal the total benefits less cost, a difference that can be divided between consumers' and producers' surplus. Price theory shows that optimal resource allocation occurs when the shadow price of the resource equals the marginal cost value of supplying it to each economic sector. This classical microeconomics tenet rests upon a number of assumptions (James and Lee 1971, Ch. 3), including:

1. Absence of artificial constraints on prices by government, labor, business, or other institutions.

2. Free movement of the resource between markets or sectors.

3. Perfect information throughout the market regarding the price of the resource.

4. Full employment of the resource.

These conditions are rarely met, but are frequently assumed as a basis for judging the efficiency of actual markets. When the above assumptions are violated, the resource is not free to travel from lower-valued uses to higher-valued uses. This situation, of course, represents an inefficient allocation of the resource.

In the western states, various institutions dealing with the allocation of water rights and the pricing of water have evolved which, at least in the short-run, violate one or more of the above assumptions. In particular, most states enforce the appropriations doctrine through institutional and legal restrictions on the sale of water or the intersectoral transfer of water rights that effectively retard the rate at which such transactions can occur. Another common problem is fixed or lagging water prices. These typically understate the real value of the resource and thereby widen the gap between supply and demand. During a period of water scarcity, these kinds of short-term restrictions tend to reduce consumer benefits. This chapter estimates such losses during a recent drought in Salt Lake County, Utah.

Problems in Estimation of Efficiency Costs of Immobility

The efficiency costs of water resources immobility can be estimated by comparing the benefits that would theoretically accrue to water users if the resource were being allocated according to free market assumptions to the benefits in fact observed under actual conditions.

If benefits are measured as the sum of consumer and producer surplus, one needs supply and demand curves. Obtaining expressions for supply and demand is made difficult by a variety of factors. First, demand for water shifts seasonally. Some causes of the shift may be stochastic in character (e.g., temperature and precipitation), thus yielding stochastic demand curves and necessitating estimation of consumer surplus as expected values. Also, during a drought situation, regulatory water conservation measures are frequently imposed and temporarily shift the demand curve. Quantitative description of these artificial shifts is quite difficult.

A second set of difficulties surrounds estimation of the resource supply. By its very nature, the hydrologic system is stochastic, and prediction of future levels of streamflow, for example, is an imprecise science. Again, one is forced to resort to estimation of expected values in order to forecast producer surplus.

Nature of the Research

This chapter documents an application of a nonlinear optimization model to estimate optimal water allocations during the 1976-77 drought in Salt Lake County. The optimal policy according to the model was contrasted to the actual water allocations observed during the drought to estimate the inefficiences produced by certain nonmarket controls. The following sections of the chapter: 1) review the reasons for short-term immobility of water resources, 2) describe the optimization model, the policy options it explores, and its specific formulation for Salt Lake County, 3) present the results of the modeling efforts, and 4) draw conclusions.

Factors Affecting Water Allocation and Use During Drought

Legal Considerations

The Appropriations Doctrine. In arid climates throughout the world, one version or another of the appropriations doctrine is frequently followed in the allocation of water rights. The appropriations doctrine has been adopted in most of the western states. The purpose of the appropriations doctrine is to protect investments in water resources development in the face of a stochastic water supply. Some others have argued that in application, however, the appropriations doctrine frequently leads to inefficient water use. For example, Meyers and Tarlock (1980) believe that appropriative rights are not easily transferred between economic sectors due to the lack of any well-defined market. They contend that water rights are simply not bought and sold freely.

A more severe criticism of the appropriations doctrine, especially from the standpoint of efficient water use in times of comparative scarcity, has been raised against the "first in time, first in right" clause (Meyers and Tarlock 1980). Under this mechanism, appropriators are senior and junior to one another along a scale from the oldest appropriation to the youngest. In times of water shortage, junior rights drop out first and lose everything before the next senior right loses anything. This fails to spread the economic risk inherent in the randomness of the water supply and violates two basic economic principles. The first involves marginal productivity. A junior appropriator who loses all his water also loses marginal units of high productivity, while a senior appropriator retains marginal units of low productivity. The second involves the pooling of risk. Meyers and Tarlock (1980) contend that under the appropriation doctrine, the individual rights are defined in such a way that the aggregate variability of supply is greater than that which nature imposes. The risks incurred in water resources development are distributed unequally.

Both criticisms of the appropriation doctrine posed above may be misdirected. First, although there does appear to be immobility in water right markets, the cause appears to be mostly due to delays in approval by state water right engineers which are required for administrative review of changes in location or type of use.

Although some delays are inevitable, the alternative to the appropriative doctrine may be a plethora of lawsuits --if the psuedo-legal authority of the state engineer did not exist--thereby causing greater delays. As to the junior-senior water right decision rule, the criticism above is valid only if one assumes that junior users are unable to rent or buy water from senior users. At any rate, water market immobility does appear to exist. An indepth discussion of whether immobility is better or worse under the appropriation doctrine vs. some other form of water law is beyond the scope of this study.

Application of appropriative rights in Utah. As applied in most states, the appropriations doctrine allows the owner of a water right to sell the right to another. The new owner may then change the point of diversion or transfer the right to a different place or kind of use subject to an administrative review designed to protect other water users from any adverse effects that may result. However, smooth operation of the water rights transfer process is frequently impeded (perhaps for good reason) by legal and institutional obstacles (see Meyers and Tarlock 1980 and National Water Commission 1973). In particular, the administrative proceedings required by most states preclude the rapid transfer of rights to meet the demands of higher-valued uses in times of drought.

In Utah, the transfer of water rights (or even the sale of water by one sector to another in substantial quantities) is accomplished through procedures analogous to those pertaining to applications to appropriate water (Hutchins and Jensen 1965). These procedures require:

1. Written application to the state engineer requesting the transfer.

2. Publication of notice of application.

3. Passage of sufficient time to allow protests, if any, to be filed.

4. Consideration of the application and any protests by the state engineer before announcement of approval or rejection of the transfer request.

The state engineer's determination is final, subject to judicial review. Accomplishing these steps may take some months, especially if junior water rights in return flow are involved. During a severe drought, passage of this much time could conceivably result in considerable economic loss. Water rights brokering services have been proposed (Bagley et al. 1980) as a mechanism for facilitating the transfer process, but at present no such service is available.

Water Pricing Policies

Demand management in the municipal and industrial sector. It is common for municipal and industrial (M&I) water supply systems to charge uniform rates over time. However, M&I water demands typically show considerable temporal variability (Linaweaver et al. 1966) as they vary with seasonal water use. In spite of the fact that the M&I sector is particularly amenable to demand regulation through pricing (i.e., the beneficiaries of the service are easily identified and those not willing to pay can be easily excluded), peak-load pricing policies are not widely used. In a series of publications, Davis and Hanke have stressed the advantages of seasonal peak load rates (see Davis and Hanke 1971, 1972; Hanke and Davis 1971; Hanke 1972).

Water supply charges are also commonly held constant over space as well as time. Since the cost of delivering water is a function of these variables, water prices should be established with reference to distance from the supply, population, density, and elevation (see Hanke 1972, Gaffney 1969, Vickrey 1969).

The water pricing options available for drought management may be analyzed from the standpoint of microeconomic theory (Whipple 1981). First, in an economically efficient system, the cost of each good will reflect the opportunity cost to society of using scarce resources to produce that good. During a normal period, the supply curve for water may be represented by S_1 in Figure 11. The demand for water is given by curve D_1. When a drought occurs, the decline in water supply can be illustrated by a leftward shift in the supply curve to S_2. As seen from Figure 11, if price is to remain constant, then measures must be taken that either increase the supply of water (thereby moving S_2 toward S_1), or reduce the demand for water (shifting D_1 toward D_2). A third option, of course, is to increase price from P_1 toward P_2.

If supply could be restored to the S_1 level, then the quantity of water supplied at price P_1 would be Q_1. However, during a severe drought it is generally difficult to implement major structural measures quickly. Outside of emergency drilling of wells and repair of leaks, relatively little can be done structurally to increase water supply. A nonstructural alternative would be for higher-valued users to purchase water from lower-valued users. This alternative, however, is complicated by the institutional inertia discussed in the previous section.

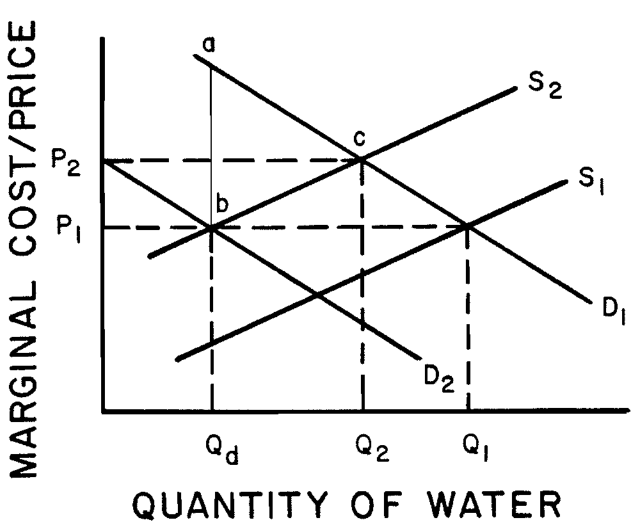

Figure 11. Supply and demand functions for water.

Increasing the price of water from P_1 to P_2 would reduce the quantity of water demanded to Q_2. However, price increases are frequently difficult to apply due to institutional and political reasons (Whipple 1981).

Reduction in demand during periods of drought, therefore, is the more common policy. From an efficiency viewpoint, however, involuntary demand reduction results in a loss of consumer benefit as compared to a policy equating marginal benefits and costs. From Figure 11, the loss in consumer and producer benefits induced by adopting an involuntary demand reduction policy rather than a policy that increases price from P_1 to P_2 is equal to the area above the S_2 supply curve within the triangle labeled "abc".

<u>Marginal cost pricing in the agricultural sector</u>. In a stinging criticism of irrigation water pricing policies, Hanke and Davis (1973) identify several ways by which alternative pricing schemes could be employed to increase the economic efficiency of irrigation. These include establishing prices as a function of actual opportunity cost and realistic interest rates and relating prices to seasonal changes in supply and demand conditions. In general, Hanke and Davis (1973) follow Gaffney (1962) in advocating streamlining the market for water rights.

In principle, the marginal cost-marginal price analysis of a leftward shift in supply offered in the previous section applies to the agricultural sector as well as to M&I. However, only a radical shift from the current "ability-to-pay" pricing criterion to a policy of cost-based pricing and the introduction of a working market for water rights will make it possible for water pricing alternatives to contribute to drought management in the agricultural sector. Institutional and political constraints presently preclude the application of effective pricing policies for irrigation water, even through increased social gains might result (Howitt et al. 1980, Kelso 1967).

A Case Study: The 1977 Drought in Salt Lake County, Utah

During the 1977 water year, much of the U.S. suffered a severe drought. In Salt Lake County the surface waters generally used for M&I supply were drastically reduced, and a variety of water conservation programs were enacted to decrease demand. The only substantial supply augmentation attempted was the drilling of new wells and increased pumping of existing wells. Relatively little was done from a drought management standpoint to change the allocation of water among sectors or to adjust water prices. Consequently, the response of Salt Lake County to the 1977 drought is a good candidate for contrasts with the response that would be expected in a true water market situation, where water management would be less dominated by short-run rigidity in water transfers and price adjustments. Salt Lake County also represents a good case study area because of relatively good data on municipal water supply and stream flow.

The Study Area

Overview. Salt Lake County covers an area of 764 square miles, of which 65 percent is valley and the rest is mountainous terrain. On the east side of the county, the Wasatch Mountain Range rises to elevations in excess of 11,000 feet. The Oquirrh Mountains border the county on the west, rising to 9,500 feet. Annual precipitation on the valley floor normally ranges from 12 to 16 inches. The county was originally settled by Mormon pioneers in 1847, who immediately began diverting water from mountain streams for irrigation.

Winter storms in the Wasatch Mountains produce accumulations of snow which result in high runoff from spring snowmelt. Much of the snowmelt also infiltrates into the soil and thereby contributes a relatively large baseflow component to Wasatch Front streams.

Water resources. On the east side of the valley, the seven major creeks are continuously gaged, with most records dating back to the turn of the century. Mean annual flow from these streams totals approximately 150,000 acre-feet. Several minor drainages also exist on the east side, and there are six minor drainages from the Oquirrh Range on the west. Because the Wasatch Range is much higher than the Oquirrhs, and because the catchments are on the windward side of the range, the Wasatch catchments receive more precipitation than the Oquirrh catchments.

The single largest source of surface inflow into the county is the Jordan River, which originates at the outlet of Utah Lake and flows north out of Utah County into Salt Lake County. The annual inflow from the Jordan River is about 260,000 acre-feet. The quality of water is too poor for municipal use, but flows are suitable for irrigation and industrial uses.

Groundwater in the county is obtained through springs and pumped wells. The valley subsurface is largely unconsolidated and acts as a large reservoir. Groundwater utilization is increasing, with present usage at about 100,000 acre-feet annually. Safe yield has been estimated at approximately 150,000 acre-feet.

Water is imported into Salt Lake County from Deer Creek Reservoir on the Provo River, from the Provo River downstream from the reservoir, and from springs in Tooele Valley. The Deer Creek and Provo River water is used for M&I purposes, the Provo River diversions are for both M&I and irrigation, and the Tooele Valley imports are used exclusively by Kennecott Copper Corporation for smelter and concentrator operations.

Water use. Municipal water use in Salt Lake County (water deliveries for domestic, commercial, fire fighting, and public service uses as well as potable water from municipal systems delivered to the industrial sector) has been rising, with withdrawals for municipal use from 1962 to 1975 increasing by about 4,500 acre-feet annually (see Table 14). Annual per capita withdrawals average approximately 0.27 acre-feet. Roughly half of the annual municipal deliveries is used outdoors for lawns and gardens.

Table 14. Historical Salt Lake County water withdrawals (1000 ac-ft).

Year	Municipal	Irrigation	Industrial
1962	197	281	a
1963	104	271	110
1964	108	276	a
1965	100	303	114
1966	127	359	120
1967	115	313	127
1968	111	296	143
1969	133	312	158
1970	120	305	153
1971	140	301	158
1972	146	306	163
1973	134	281	177
1974	160	311	170
1975	143	277	139
Average	125	299	144[b]

[a]Not available
[b]12-year average

Industrial water use has been increasing at a rate of roughly 1000 acre-feet per year and presently stands at about 160,000 acre-feet per year. The largest industrial user is Kennecott Copper Corporation.

Agricultural use includes irrigation and stock watering. Diversions for irrigation show a slight downward trend in recent years, and irrigated acreage has undergone a much more pronounced decrease (see Tables 14 and 15). Dividing 1975 irrigation diversions by estimates of the total irrigated acreage for that year gives an approximate diversion of 7.9 acre-feet per acre. A more realistic application, considering typical efficiencies and water requirements, would be 5 acre-feet per acre.

Optimization Model

Subregional County Divisions

In order to achieve as much spatial resolution as possible in assessing drought impacts, the study area was divided into seven subregions as indicated in Figure 12. These subregions were chosen following the work by Bishop et al. (1974, 1975), Narayanan et al.

Table 15. Historical Salt Lake County irrigated acreage.

Year	Irrigated Land (1000 acres)
1935	48
1955	44
1975	35

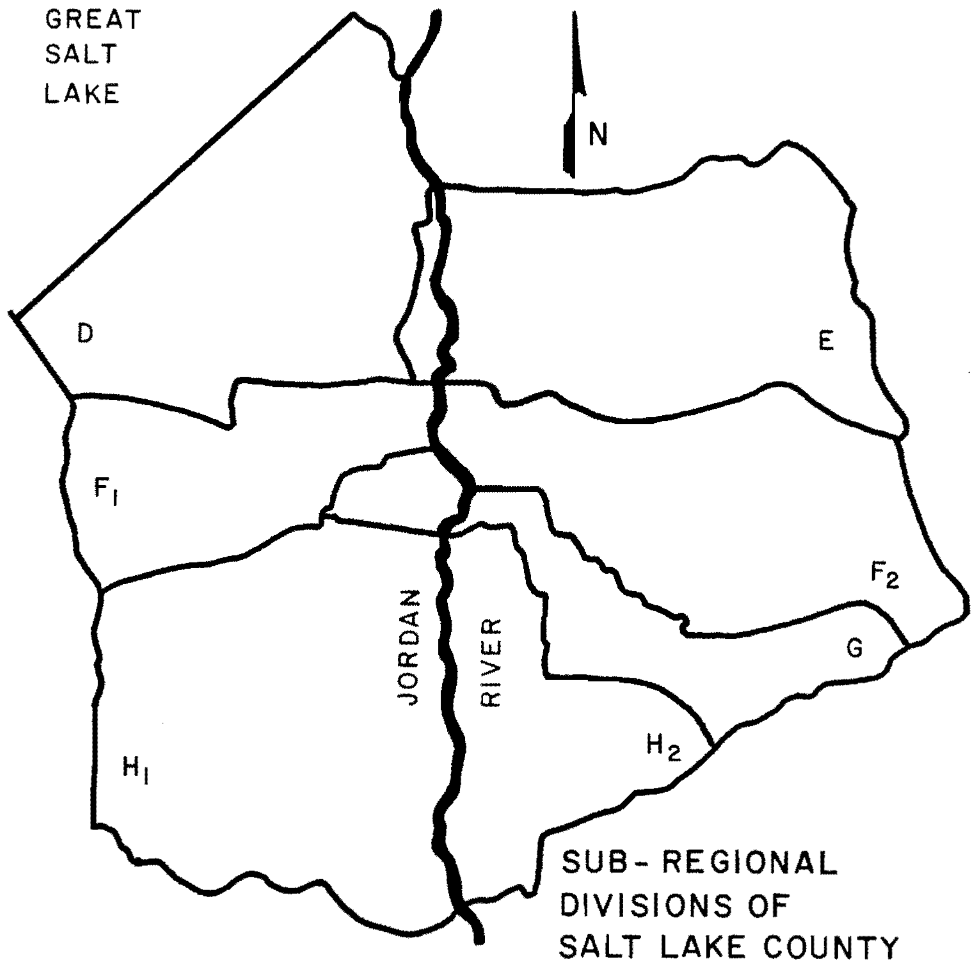

Figure 12. Subregions used in the Salt Lake County case study.

(1976), and Pratishthananda and Bishop (1977). The subregions were formulated so as to constitute as coherent a unit as possible considering watershed subbasins, water supply distribution systems, and water district boundaries. All water supply and use data for the optimization model were specified at the subregion level.

Objective Function

The objective function used in the optimization is maximization of the net benefits of water use in the M&I and agricultural sectors.

Estimation of municipal benefits. The total benefits of water use in the municipal sector were expressed as the sum of the areas under each of five municipal demand curves (one for each of the months of May through September) for each subregion of the model. Referring to Figure 13, total municipal benefit, M_B, can be expressed as:

$$M_B = \sum_t \sum_r \int_0^{Q^*_{rt}} CM_{rt} \, Q^{-\alpha_{rt}} \, dQ$$

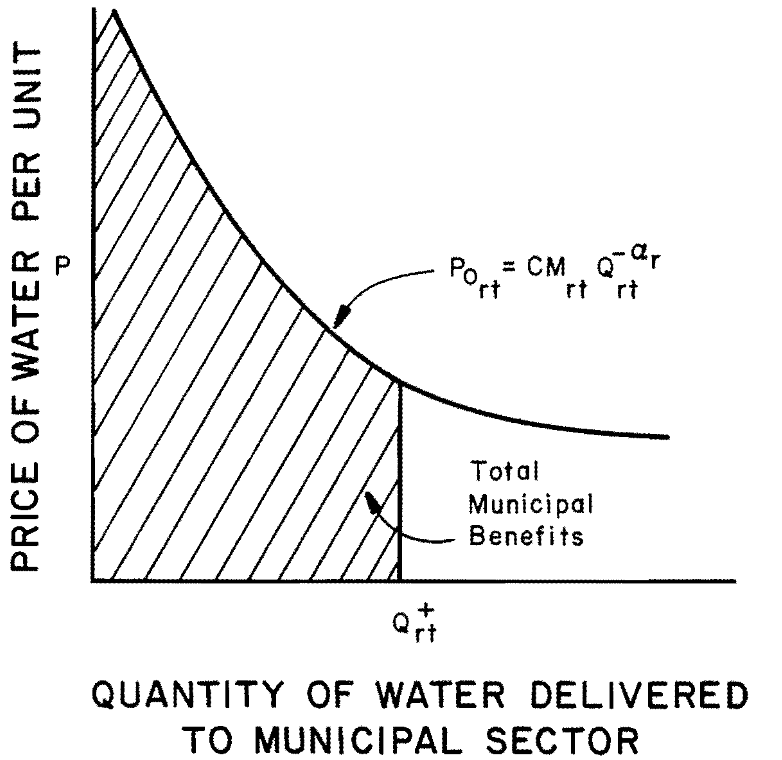

Figure 13. Estimation of gross municipal benefits.

where t=1, ..., 5 is an index on months, r=1, ..., 7 is an index on county subregions, CM_{rt} is a parameter for the region determined from monthly temperature and precipitation, α_{rt} is the inverse of demand elasticity, and Q_{rt}^* is the quantity of water delivered for the municipal sector in the rth subregion in the tth season.

Demand curves for the municipal sector were estimated from monthly precipitation, temperature, and daylight hours data as recommended by Hansen (1981) and Hansen and Narayanan (1981). They propose municipal demand curves having the formulation:

$$D = \beta_0 + \beta_1 I + \beta_2 T + \beta_3 P + \beta_4 L$$

where D is the natural logarithm of water demand, β_1 are coefficients, I is the natural logarithm of monthly rainfall, T is the logarithm of mean monthly temperature, P is the logarithm of marginal price of water, and L is the logarithm of the percent of the annual daylight hours in the month. The weather stations that were selected to represent the various subregions are listed in Table 16, together with the mean precipitations and temperatures for the months of May through September as well as the values observed in 1977. Table 17 presents the demand curves that were estimated for the subregions for each of the seasons, using both mean and 1977 temperature and precipitation data.

Estimation of agricultural benefits. Agricultural benefits are expressed as gross revenues from the sale of commodities less the costs of production, exclusive of water delivery costs. Farm budgets published in the Utah Agricultural Census for 1974 through 1976 were used to obtain average crop production costs and sale prices. These averages were used in the model.

Table 16. Subregion climatic characteristics.

Subregion	Representative Weather Station	Monthly Temperature (°F)										Monthly Precipitation (inches)									
		May		June		July		August		September		May		June		July		August		September	
		Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977
D. Magna area	Garfield	60.65	55.7	65.81	75.9	79.67	78.0	77.23	75.8	66.73	66.6	1.64	3.62	1.41	4.76	0.57	3.79	0.72	0.94	1.08	1.73
E. Salt Lake City area	Salt Lake City Airport	59.28	55.0	67.84	73.2	77.13	77.3	74.69	75.0	64.31	66.4	1.38	4.76	1.13	0.06	0.70	0.61	0.89	1.85	0.85	1.85
F_1. Hunter-Granger area	Salt Lake City Suburban Sewage Plant	59.65	55.4	67.90	71.3	76.51	76.2	74.55	74.0	64.81	65.6	1.33	3.79	1.08	0.00	0.88	0.82	0.68	1.49	0.84	1.34
F_2. South Salt Lake area	a	a										a									
G. Murray area	a	a										a									
H_1. West Jordan area	Bingham Canyon	54.61	52.3	62.88	71.1	72.51	74.4	70.20	72.4	61.79	64.1	1.92	4.84	1.84	0.43	1.06	1.39	1.16	1.72	1.11	1.90
H_2. Draper area	Cottonwood Weir	60.47	55.3	69.29	75.7	79.55	77.9	77.27	75.7	67.80	68.9	2.04	6.77	1.45	0.31	0.67	2.03	1.15	2.12	1.34	3.39

[a]Same weather station as F_1 subregion.

Table 17. Estimated municipal demand curves by subregion.

Sub-region	Elasticity[b]	Estimated CM Values[a]									
		May		June		July		August		September	
		Mean	1977	Mean	1977	Mean	1977	Mean	1977	Mean	1977
D	-0.138	505.83	417.83	574.17	636.92	840.49	693.69	741.11	705.09	504.09	483.08
E	-0.469	51548	42453	63720	86097	82566	83568	73748	70915	52103	52211
F_1	-0.138	2593.4	2131.2	3173.0	6165.5	3941.4	3941.8	3651.5	3379.4	2547.7	2492.5
F_2	-0.469	26770	22352	32878	54704	41262	41181	38392	36149	27111	26844
G	-0.469	23837	19903	29277	48712	36742	36670	34186	32189	24141	23904
H_1	-0.138	635.29	551.50	778.86	1053.5	1031.2	1045.7	918.18	928.94	667.07	671.98
H_2	-0.138	1610.6	1277.2	2009.0	2605.1	2694.7	2378.8	2320.7	2137.8	1650.5	1561.5

[a]Demand for water is expressed as $Q = CM\ P^{-\alpha}$ where Q is in acre-feet per month, CM is given above, P is price in dollars per acre-foot, and α is elasticity.
[b]From Hansen (1981).

seasonal crop consumptive use requirements.

Results

Overview of Model Runs

Five runs were made with the model, each representing a different set of constraints on the water market as well as different assumptions about the stochasticity of the hydrologic system. The first two runs represent free-market responses to drought. The first run was made using the iterative approach discussed previously, where expected values of municipal demand and surface supply for future seasons condition the solution of each successive iteration. The second run uses the actual hydrologic conditions and M&I demands for 1977 as inputs.

The remaining three runs are also deterministic in terms of water demands and hydrology, but each represents a departure from free-market conditions in terms of an artificial shift in the demand for water and/or imposition of constraints to movement of the resource between economic sectors. The third run constrains the M&I water use to quantities approximating those observed in Salt Lake County during the 1977 drought. These quantities were considerably less than normal and resulted from the application of a variety of demand reduction techniques. The fourth run assumes no demand reduction, but requires that the irrigation water rights on Wasatch Front streams not yet covered by exchange agreements be delivered in full to the agricultural sector. Finally, the fifth run assumes both demand reduction and maintenance of agricultural water rights east of the Jordan River. As such, it represents an approximation of the actual institutional situation that prevailed during the drought. Table 21 summarizes the principal characteristics of these five runs.

Optimization Results

The solutions were obtained using the Modular In-core Nonlinear Optimization System, a nonlinear optimization package developed by the Department of Operations Research, Stanford University. The results are summarized in Table 22. The total net benefit from water use ranges from $47.86 million for run five to $53.23 million for run two. The run that performed best represented a free-market given perfect knowledge of hydrologic conditions. The run which produced the least consumer plus producer surplus was the most constrained in that it limited water movement between sectors as well as supplies to M&I. In between these extremes, additional constraints reduced the net benefits.

Table 21. Summary description of model runs.

	Treatment of Hydrologic Conditions		Constraints Applied to Water Market		
Run	Stochastic	Deterministic	None	Water Conservation in M&I	Irrigation Water Rights Maintained
1	X		X		
2		X	X		
3		X		X	
4		X			X
5		X		X	X

through September). M&I and agricultural demands are also forecast from the basis of expected monthly temperatures and precipitation amounts. These forecast supply and demand quantities are put into the model, and a solution is obtained. At the end of the next month (May), new supply and demand quantities can be forecast for the remaining months. These new forecasts are entered into the model, along with the optimal policies (in terms of water prices, reservoir releases, etc.) that were identified for May. At this point, another solution is obtained to find the optimal water management policies for June, conditional upon the expected values of future supplies and demands. The process is continued, month-by-month, with each iteration resulting in identification of conditionally optimal management policies and new estimations of expected future supply and demand conditions.

Expected Values of Random Variables

A multivariate analysis of the streamflows from the gaged Wasatch Front streams was conducted following the procedures recommended by Salas et al. (1980, Ch. 7). This analysis was performed on monthly streamflow data for the water years of 1947 through 1976. Identification and estimation of autoregressive moving average (ARMA) models for the surface supplies was done using the Box-Jenkins procedure available on the Statistical Package for the Social Sciences. The multivariate model is of the form

$$\bar{Z}_t = \sum_{i=1}^{P} \phi_i \bar{Z}_{t-i} + \bar{\varepsilon}_t - \sum_{j=1}^{8} \theta_j \bar{\varepsilon}_{t-j}$$

where $\bar{Z}_t$ is a vector of standardized flows for season t, $\bar{\varepsilon}_t$ is the vector of error terms for time t, and ϕ_i and Θ_j are, respectively, the autoregressive and moving average matrices of lags i and j. The procedure recommended by Salas et al. (1980) yields a model where the ϕ and Θ matrices are diagonal, and the cross correlations are preserved in ε_t only at lag-zero. In this approach, $\bar{\varepsilon}_t$ becomes

$$\bar{\varepsilon}_t = \sigma_\varepsilon^2 \, B \, \xi_\tau$$

where σ_ε^2 is the error variance, ξ_t is a column vector with standardized elements that are independent in time and space, and B is a square matrix that is estimated from $\hat{B}$, where

$$\hat{B}\hat{B}^T = \hat{M}_O$$

where $\hat{M}_O$ is the lag-zero cross-correlation matrix.

Table 20 presents the estimated values of ϕ and Θ for each of the surface streams.

Expected Demands

The expected municipal demands were estimated from mean monthly precipitation and temperatures. These curves are given in Table 17. Expected irrigation demands were expressed in the model by netting effective precipitation from the

Table 20. Estimated ARMA coefficients for Wasatch Front streams.

Stream	ϕ	θ
City Creek	0.80453	-0.16475
Emigration Creek	0.85127	0
Parleys Creek	0.88258	0.18343
Mill Creek	0.86700	0
Big Cottonwood Creek	0.57127	-0.26098
Little Cottonwood Creek	0.56091	0

as representative of the general seasonal probability observed on gaged streams for Salt Lake County as a whole for the 1977 water year. Limited surface water storage is available in three small reservoirs in watersheds on the Wasatch Front. These reservoirs and their capacities are listed in Table 19. The model contains storage constraints to allow seasonal carry-over consistent with the capabilities of these reservoirs.

Agricultural production. The model includes constraints which express agricultural production and water consumption for each subregion. The production constraints are of the form

$$Y_c = \sum_i P_{ic} L_{ic}$$

where Y_c is the yield of the cth crop, P_{ic} is the productivity of the cth crop on the ith land class, and L_{ic} is the amount of land in class i allocated to crop c. Four land classes consistent with SCS designations were included in the model.

Water consumption constraints were written for each season as

$$\sum_i \sum_c q_{ct} L_{ic} \leq Q_t$$

where c is an index on crops, t is an index on seasons, q_{ct} is the per acre consumptive use water requirement (adjusted for seasonal precipitation) for the cth crop for the tth season, L_{ic} is the amount of land assigned to the icth crop in land class i, and Q_t is the amount water available for irrigation in the tth season, adjusted for conveyance and application efficiences. Crop rotation constraints as recommended by Anderson (1972) were also included.

Solution Process and the Expected Values of Stochastic Variables

Solution Process

Water planners do not have perfect information when they make decisions. Decisions on releases must consider expected future inflows as well as probable future demands. Since both supply and demand are stochastic, an iterative approach was taken to obtain an optimal water supply allocation, with each iteration estimating the optimal values of control variables for the next season. The iteration process proceeds as follows.

At the end of the winter season (April 30), the values of the streamflows are known. These are used to forecast expected values of streamflows for the following five months (May

Table 19. Capacities of major Salt Lake County reservoirs.

Reservoir	Stream	Capacity (ac-ft)
Mt. Dell	Parleys Creek	3400
Lake Mary	Big Cottonwood Creek	740
Twin Lakes	Big Cottonwood Creek	940
Lower Bells Canyon Reservoir	Bells Canyon Creek	420

Crop yields by land productivity class specified by Anderson (1972) were used to estimate production for each of eight crops. Seasonal water requirements for these crops were obtained from Anderson (1972) and from published crop consumptive use requirements for north-cental Utah (SCS 1976).

In general, agricultural benefits can be computed as:

$$B_A = \sum_c \sum_r \sum_i a_c \, Y_{cri} - k_c \, L_{cri}$$

where B_A is the net benefit of agricultural production, net of water supply costs, c is an index on crops, r is an index on subregions, i is an index on land classes, a_c is the sale price of the cth crop, Y_{cri} is the total yield of the cth crop in the rth subregion from the ith land class, k_c is the cost of land preparation, harvesting, etc., for the cth crop, and L_{cri} is the amount of land allocated to the cth crop, rth subregion, ith land class.

The crops considered were:

1. Full season alfalfa
2. Partial season alfalfa
3. Barley
4. New alfalfa with a barley nurse crop
5. Corn silage
6. Sugar beets
7. Pasture
8. Wheat

Water supply costs. The supply costs were estimated from Salt Lake City Water Department budgets contained in the annual reports. In general, water supply costs reflect the costs of collecting the water from a source and transporting the water to a destination for use or for treatment. Table 18 shows estimated costs of water supply from various sources.

Table 18. Estimated water supply costs for various sources.

Source	Cost ($/ac-ft)
City Creek	81.02
Parleys Creek	73.60
Big Cottonwood	66.71
Little Cottonwood	71.34
Deer Creek Imports	86.73
Wells	78.75

Model Constraints

Water supply. Water supply to the M&I sector within a subregion for a given season is bounded by the total water available from other subregions minus exports to other subregions. In general, the major surface water supplies for the M&I sector come from the six Wasatch Front streams and Deer Creek Reservoir. Irrigation water is limited to the total water available from canal systems diverting water from the Jordan River, from wells, and from other surface water sources. The agricultural sector maintains some rights on mountain streams that produce water of a quality suitable for treatment and distribution to the M&I sector. Under a true market situation, this water is available for sale for M&I uses.

The model places total annual limits for each subregion on the amount of well water that can be extracted. These limits were obtained from Bishop et al. (1975). Surface waters on ungaged streams available in any given season for usage by the appropriate economic sectors are estimated as the 90 percent probability flows as published by MWDSC et al. (1982). This probability was selected

Table 22. Summary of solution results for five model runs.

Run Number	Total Net Benefit ($\$10^6$)	Groundwater Use for M&I (1000 ac-ft)	Wasatch Front Water for M&I (1000 ac-ft)	Wasatch Front Water for Irrigation (1000 ac-ft)	Net Agricultural Benefit ($\$10^6$)
1	53.20	45.6	52.9	1.8	2.4
2	53.23	44.5	53.1	1.7	2.4
3	47.87	25.5	42.1	6.1	2.3
4	53.17	51.0	44.8	10.2	2.4
5	47.86	28.5	39.1	10.2	2.3

Both free market runs (with perfect knowledge and stochastic information respectively) performed better than any of the runs involving water conservation or maintenance of irrigation water rights on Wasatch Front streams. In interpreting these figures, the absolute numbers given as benefit estimates are not accurate since the M&I demand curves are hyperbolic. One should compare differences.

The two free market runs gave similar results. The first run has slightly lower net benefits and small differences in the distribution of water use by source. It is interesting that the iterative approach to stochasticity of supply and demand used in the first run provides a solution nearly identical to that resulting from assumptions of perfect knowledge of future hydrologic conditions.

The fourth run, involving maintenance of irrigation water rights but no water conservation measures, produces benefits similar to those from the two free market runs. It replaces the surface water lost to M&I because of prior rights to agriculture by additional groundwater usage to augment the reduced surface supplies. Groundwater pumping is greatest in the fourth run because both demands and surface water constraint were greatest.

The third and fifth runs employ measures to reduce demand in the M&I sector and show about five million dollars less benefits. Since the agricultural benefits are nearly the same, most of the reduction must be attributed to losses of consumer and producer surplus resulting from the induced artificial shift in the M&I demand curves.

Water Pricing and Hydrologic Stochasticity

Table 23 summarizes the model estimates of optimal water prices for the M&I sector for selected locations in the county as computed for the first run (applying an iterative approach to variability in the surface inflows). The model raises M&I water prices as the growing season progresses. Price increases from the first month to the last are approximately $0.10 per 1000 gallons. These changes reflect shifts in both demands and supplies as the summer months pass. The price shifts would be far less pronounced if more storage were available in the water supply system so that excess high surface flows in the early months could be saved for higher demands in later months. To an extent, the model uses the groundwater system for this purpose.

Table 23. Optimal water prices at selected locations assuming stochastic inflows.

Location	Optimal Water Prices ($/ac-ft)				
	May	June	July	August	September
Salt Lake City	93.71	106.82	113.78	127.45	127.45
South Salt Lake	66.71	79.82	86.78	100.45	100.45
Granger-Hunter	97.04	97.04	104.55	104.55	104.55
Murray	71.34	71.34	78.85	78.85	78.85

Conclusions

The two institutional factors suspected of reducing benefits to water users during times of drought were inflexibilities in water pricing (i.e., inability of the water supply institutions to deliver water at a price equal to marginal cost) and sluggishness of market response to reallocate water to higher valued uses. These two problems are studied in the context of the 1977 drought in Salt Lake County.

Optimization of the agricultural water use indicates that irrigation rights exceed the water needed for efficient crop production. This has come about through a decrease in farm acreage over the years without a corresponding decrease in water rights. However, continued irrigation diversions of waters of a quality suitable for treatment and use in municipal supplies did not significantly reduce the economic benefits. One reason is that little surface storage is available to hold excess spring runoff for later M&I use. Also, the smaller quantities of high-quality water that go to agriculture later in the year are easily replaced with inexpensive groundwater. Higher relative prices for groundwater pumping would change this.

The largest efficiency losses resulted from inflexibly holding to the lower prices set for normal water availability conditions and the restrictions to municipal use that artificially reduced demand to the amount of water available. The reduced use resulted in a fairly substantial revenue loss (decline in producers surplus), but the greater portion of the $5 million loss was in consumer surplus and associated with large quantity shifts on a demand curve of low elasticity.

These observations indicate that the largest gains through more efficient water allocation during drought, at least in the study area, are probably to be realized from allocating the reduced water supplies by raising prices. Whether temporary price increases are institutionally feasible or even worth the cost of implementing needs to be explored. If more flexible pricing policies are to have an impact on water demand, the market must be sensitive to short-term price changes. Residential users would have to be made aware quickly of any price changes. This would require rapid mechanisms for distributing price information.

CHAPTER V

SUMMARY AND CONCLUSIONS

The very severe one-year drought of 1976-77 brought forth a large array of drought relief/management programs from every level of government as well as from individual water utilities. In retrospect the management policies such as pricing, public education, and various rationing concepts at the level closest to the water users (water companies, associations, districts, municipalities, etc.) added motivation for conservation that resulted in sharing the shortages.

The large majority of government relief programs in contrast provided capital for water development investments which were not usable during the 1-year drought, but which will provide benefits during future dry years. In this regard, an important reason for such small losses in the western states during this very severe drought was that the much more serious hardships experienced during the long drought in the 1930s and other dry periods since had caused a political climate favorable to water development during previous decades. As a result, substantial carryover storage volumes in major reservoirs throughout the west at the beginning of 1977 reduced losses that would otherwise have been much more extensive and severe.

Some government relief programs, however, did produce important benefits during the emergency. An example was the state emergency stock water program in Utah. This effort provided portable tanks on loan (mostly from military bases) to ranchers so that water could be hauled to stock in grazing areas. Federal programs such as the ASCS emergency stock feed program and the U.S. Bureau of Reclamation water rental programs also provided important relief when it was needed.

Management Policies in the Municipal Sector-- What Worked?

Specifically in Utah, the three most common rationing policies were 1) restrictions on time for outdoor use (24 of 33 systems sampled used this policy); 2) price increases (9 of 33 systems); and 3) mandatory quantity restrictions (5 of 33 systems). Four systems in the sample used both time and quantity restrictions.

A regression model applied to these data gave the following information on policy effectiveness:

1. A reduction of 1 hour per week in the time in which outside watering is allowed decreases total water use by 1.27 gallons per day for a typical connection using 1000 gallons per day. For connections with higher use levels, the reduction will be greater. In contrast, utilities with voluntary restrictions sometimes (3 of 9 cases) experienced increased rather than decreased use. A reasonable hypothesis is that water users perceive voluntary restrictions as a forerunner of mandatory restrictions and therefore attempt to soak their landscaping in preparation for that occurrence.

2. A price increase of 1 percent leads to a 1/10 percent decrease in the quantity of water consumed. A price elasticity that is lower during drought than in normal times suggests that users' behavior (demand function)

changes during what they perceive as a short term emergency and that moderate price increases are not so effective in managing consumption during droughts as during normal periods. Short run adjustments are harder to make than long run changes. However large price increases had major impacts on use. A major system which charged a \$10/1000 gallon price for exceeding mandatory quantity limits experienced a 50 percent decrease in use.

3. For every 1000 gallon reduction in the maximum allowable monthly water use, a reduction in use of 4.46 gallons per day was observed.

From an economic efficiency point of view, mandatory restrictions on total monthly use are probably a better choice than mandatory outdoor time restrictions since the former allows users to allocate water between indoor and outdoor use as they choose. However, both of these appear to be more effective in reducing water use than moderate increases in price. It would take a 200 percent price increase to produce a 20 percent reduction in water use.

Nonprice Rationing in the Municipal Sector

A model was presented for determining the optimal long term price schedule for rationing a stochastically variable water supply during the summer peak demand season among groups of municipal customers which have different demands. This model was applied to the Salt Lake City water system using historic data to simulate demand functions for four classes of users and the system's supply function. Prices were obtained for both a block rate pricing policy and a uniform rate policy.

An interesting results was that consumer surplus is maximized by a decreasing block rate, that is, supply best matches demand when groups of users who consume larger quantities of water pay a lower average price than groups who use smaller quantities of water. It was also found that the current average price for water in Salt Lake (\$0.25 per 1000 cubic feet) is very close to optimal, given their current array of water sources.

Inefficiencies of Short Term Water Immobility During Drought

A third model analyzed various drought management policies in terms of their impact on net benefits to agricultural and municipal water users. The model has the capability to modify policies monthly with a changing hydrologic situation. It is designed to optimize pricing policy and source selection (groundwater vs. surface water for example). The model as applied to Salt Lake County with constraint sets varying from total freedom for water exchanges between sectors with unlimited price changes to institutional constraints and flow matching those prevailing during the 1976-77 drought.

Results for Salt Lake County suggest that a large loss (about \$5 million) in benefits (mostly consumer surplus) occurred during the drought due to inflexible prices. Optimal municipal water prices would have varied from \$71 to \$127. The stochastic portion of the model makes excellent policy choices when operated in a mode of monthly policy corrections to match updated hydrologic conditions. The results were very close to those where perfect knowledge of future hydrology was used.

This model should provide an excellent tool for judging water management policies in other locations, both in terms of planning for drought and for more typical conditions.

Overall

Based on the case of water management during the 1977 drought in Salt

Lake County, mandatory water use regulations proved much more effective than price increases in reducing water use to match the smaller supplies. A theoretical analysis of the demand and supply functions showed the current pricing schedule to be about optimal. A third model showed that there were substantial economic losses, largely reduced consumer surplus for residential users, associated with the 1977 regulations. This combination of results obviously suggests a need for research on either restructuring drought water use regulations so that the reductions better match uses of low economic value or on how to implement changes to water price in a way that makes the public more responsive in the short run. Nonstructural water conservation programs need to be predesigned from information on the costs and results of various alternatives so that they are not hastely thrown together during drought emergencies.

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APPENDIX

1976-77 DROUGHT RELIEF ACTIVITY SUMMARY

Sector: Municipal/Domestic — Local Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Mandatory restriction to 50 percent of normal outdoor use ($10/K gal penalty for violation (also time restrictions)	Very good - almost no violation	Large decrease in revenue. Some landscaping destroyed due to fear of penalty. Increase to above normal use during month following lifting of restrictions	Salt Lake County (Utah) Water Conservancy District	Hughes et al. 1978
Public education (on conservation) via messages enclosed with monthly bill	Good response revealed in post drought survey			
Supply increase - drilled more wells				
a. Time limitation for outdoor use b. Quantity limits c. Price increases d. Public eduction	Variable results (see regression analysis section)		Miscellaneous Utah cities and towns	Hughes et al. 1978

Sector: Municipal/Domestic | Local Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Reduce use: voluntary demand conservation program	Fairly effective	Decreased revenues in face of rising maintenance costs; but one town increased revenue. Drought impacts tend to uncover or exacerbate existing problems	Small cities, Colorado	Howe et al. 1980
Reduce use: price increases Damage reduction/recovery; price increases to generate revenues for maintenance and repair	Revenues increased but use reductions were mixed. Sharp increases most effective in short run	Metering improves price responsiveness		
Augment supply: short-term exchange, truck in water, system repair, wells				
Reduce use: various outdoor watering restrictions	20 percent expected reduction in withdrawal		Ft. Collins, Colorado	Anderson 1980
Reduce use: mandatory quantity restrictions	57% reduction requirement was not by 70% reduction		Marin Munic. Water District	Larkin 1978
Reduce use: mandatory quantity restriction	30% needed reduction was met	Salinity problems		Larkin 1978
Damage reduction/recovery: change point of withdrawal to hgher quality location	Preserved quality of intake at acceptable levels	Organizational cooperation allowing use of canal for conveyance		

Sector: Municipal/Domestic				Local Initiatives
Program Design	**Effectiveness**	**Constraints and Side Effects**	**Program/System Identifier**	**Reference**
Reduce use: mandatory use reduction of 25% Augment supply: purchase from state water	57% reduction	 Organization and facilities to reallocate supplies over large area	San Francisco Water Dept., Calif.	Larkin 1978
Reduce use: mandatory 35% use reduction Augment supply: accelerate development underway; move point of diversion of supplemental supply	47% reduction	 Organizational co-operation	East Bay Municipal Utility Dept., Calif.	Larkin 1978
Augment supply: purchase from state water	Satisfactory	Organization co-operation to secure release of water and inter-connect systems	Marin Municipal Water District	Larkin 1978
Reduce use: install meters and flow restrictors on faucets, increasing price	33% reduction in household use in hypo-thetical western urban system	Reductions in return flows, revenue losses from reduced use more than offset by revenue increase from price hike	Hypothetical	Flack 1981

Sector: Municipal/Domestic State Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Reduce use, augment supply Damage reduction and recovery: public information program, technical assistance		Late implementation Too much effort directed long-term actions, not immediate impacts.	Colorado	Howe et al. 1980
Emergency grants for facilities (mostly wells to increase water supply)	33 systems were granted $855,000		Governor's Culinary Grant Fund	Hughes et al. 1978
Revolving Fund with subsidized loans for renovation-expansion of municipal systems	$1,000,000 added to this on-going revolving fund program		Cities Water Loand Fund	
	Most increased water production capacity was not usable during the drought			

Sector: Municipal/Domestic — Federal Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Augment supply: grants and loans to drought impacted water systems with population $> 10{,}000$	\$175 million on 268 projects, most in west questionable results	Late implementation inadequate standards for determining project worthiness, inadequate coordination with other programs	Economic Development Administration Community Emergency Drought Relief Program	Comptroller General of the United States 1979
Augment supply: grants and loans to drought impacted water systems with population $< 10{,}000$	\$224 million on 595 projects questionable results	Same as above	Farmers Home Administration: Community Program Loans and Grants	Comptroller General of the United States 1979
Damage reduction/recovery Augment supply: FmHA and EDA loans		Late implementation Tended not to be immediate drought related, but rewarded poorly managed systems	FmHA and EDA/ Colorado	Howe et al. 1980

Sector: Agriculture			Local Initiatives
Program Design	**Effectiveness**	**Program/System Identifier**	**Reference**
Allocation of water to fewer acres, lining of ditches, supply termination to junior water right owners	Some areas actually increased yields due to better soil planted and ideal summer rains; but many areas suffered large losses in both annual and some perennial crops	Irrigation companies, districts, and individual farms in Utah	Hughes et al. 1978
Construction of wells and reservoirs to increase supply	Too late for help during 1977 but should produce future benefits		
Accelerated sale of stock due to inadequate range condition	Number of beef cattle were reduced by 50 percent in two counties - including some breeding stock	Stockmen in Utah	Hughes et al. 1978

Sector: Agriculture — Local Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Augment supply: installation of irrigation systems/dry land conversion			Georgia, South Dakota	Matthai 1979
Augment supply: well drilling, increased groundwater use		Declining water tables, increased pumping costs, subsidence	South Dakota, Nebraska, Utah, Kansas, Nevada, Idaho, Oregon, California, Georgia	Matthai 1979
Reduce use: plant later, reduce acreage, plant crops with lower water requirements				Matthai 1979
Reduce use: divert winter use to storage, crop reductions, increased application monitoring, reduce conveyance loss	In some cases, more careful application reduced use and improved yields	Highly developed basins performed much better where cooperative attitudes were widespread	Colorado	Howe et al. 1980
Augment supply: well drilling, trucking in water for domestic supply and stock, temporary exchanges and rentals, cloud seeding	Efficient short term allocation should result from unimpeded rental market, unless return flows are important			

Sector: Agriculture			State Initiatives
Program Design	**Effectiveness**	**Program/System Identifier**	**Reference**
No interest loans to irrigation companies	Fund was increased by $3.5 million	Revolving Construction Fund	Hughes et al. 1978
No interest loans to stockmen	$2 million appropriated (not all used)	Stockwater Loan Program	
Increase in normal cloud seeding program	$300,000 allocated but $100,000 returned (few clouds to seed)	Emergency Cloud Seeding Program	
Public education on drought condition and conservation techniques		Drought Information Center	
Tanks and vehicles acquired on loan basis mostly from military	689 portable tanks were placed in use (saved much of breeding stock)	Stockwater Hauling Program	

Sector: Agriculture				State Initiatives
Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Reduce use, augment supply Damage reduction and recovery: public information program, technical assistance		Late implementation Too much effort directed long-term actions, not immediate impacts.	Colorado	Howe et al. 1980

Sector: Agriculture — Federal Initiatives

Program Design	Effectiveness	Program/System Identifier	Reference
Grants of 80 percent of cost for water conservation and development projects	$11.8 million to 6,000 farmers in Utah) Total in Multistate Drought Region = $100 million	ASCS-Emergency Conservation Measures Program	Hughes et al. 1978
Up to 50 percent of eligible livestock feed cost provided as a grant	$5.1 million provided to Utah farmers	ASCS Emergency Feed Program	Hughes et al. 1978
Emergency low interest loans to cover losses to farmers	$100 million	Farmers Home Administration (FmHA) Emergency Loan Program	Hughes et al. 1978
Loan and grant program for short term water supply assistance to communities under 10,000 population	$150 and $75 million in loans and grants respectively	FmHA-Community Facilities Program	Hughes et al. 1978
Federal crop insurance (FCIC) program	$50 million increase in FCIC capital stock	Federal Crop Insurance Corp.	Hughes et al. 1978
5 percent loans for water supply and conservation measures and establishing a water bank for reallocation of water	$100 million	Bureau of Reclamation Drought Emergency Program	Hughes et al. 1978
Emergency irrigation loans	$30 million	Bureau of Reclamation Emergency Fund	Hughes et al. 1978
Purchase of emergency power supplies	$13.8 million	Southwestern Power Administration Community Drought Relief	Hughes et al. 1978
Loans and grants for short term water supply assistance to communities over 10,000 population	$175 million loans and grants	Economic Development Administration Cummunity Drought Relief	Hughes et al. 1978

Sector: Agriculture | Federal Initiatives

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Damage reduction/recovery: USBR nonprofit brokerage in California	Not successful	Legal uncertainties for buyers and sellers. Incomplete jurisdiction over water rights. Physical capacity to transfer.	Bureau of Reclamation, Emergency Act of 1977, California	Robie 1978
Damage reduction/recovery: implement water bank to shift surplus and annual crop water to higher value uses	$74 millon on 493 projects, most in Far West	Late implementation Inadequate standards for determining project worthiness/relation to drought	U.S. Bureau of Reclamation: Emergency Drought Act of 1977	Comptroller General of the United States 1979
Augment supply: permit projects to develop new sources, increase utilization of existing facilities	Questionable results claims moderate success for water bank in California	Inadequate coordination with other programs Insufficient administrative capacity		
Damage reduction/recovery: loans to farmers for repairs, crop losses, and working capital	$3,025 million for 92,601 loans Uncertain results	Inadequate coordination with other programs	Farmers Home Administration Consolidated Farm and Rural Development Act Emergency Loans	Comptroller General of the United States 1979
Damage reduction/recovery: loans to business, farmers, nonprofit organizations for damage repair, current facilities, and working capital	$1,556 million for 40,601 loans (not all drought related) Some questionable results	Late implementation Inadequate standards for determining project worthiness. Inadequate coordination with other programs	Small Business Administration: Small Business Act disaster loans	Comptroller General of the United States 1979
Damage reduction/recovery: FmHA and SBA loans	Little short-term effect	Late implementation Early termination/inadequate follow-up Funds not directed to immediate drought effects. Grant process too complex	EDA and FmHA/Colorado	Howe et al. 1980

Sector: Wastewater

Program Design	Effectiveness	Constraints and Side Effects	Program/System Identifier	Reference
Reduce use: public information programs on conservation techniques, price increases, and use restrictions	20-60% use reductions. Wastewater flows decreased an average 18% in 14 Calif. communities	Sharp, unanticipated waste flow reductions increase wastewater system operating costs and reduce operating efficiency by: accumulation of sediment, hydrogen sulfide formation, and clogging in collector system; shock loads of grit, odor problems, ineffective solids removal, high concentration wastes in treatment facilities. Planned conservation (with design changes) could lead to lower costs for collection and treatment.	Colorado	Howe et al.